Certification of Translation

(Japanese Patent Application No. 11-259,615)

I, the undersigned, Sawako KODAMA residing at 1-25-5-204, Yutenji, Meguro-ku, Tokyo 153-0052, JAPAN do solemnly and sincerely declare that I am well acquainted with the Japanese language and the English language and that the attached English translation of the Japanese Patent Application No. 11-259,615 filed September 13, 1999 is an accurate translation to the best of my knowledge and belief from the Japanese language into the English language.

Date: March 9, 2006

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[DOCUMENT NAME] SPECIFICATION

[TITLE OF THE INVENTION]

WAVELENGTH STABILIZING CONTROL METHOD AND LIGHT SOURCE UNIT, EXPOSURE METHOD AND EXPOSURE APPARATUS, AND DEVICE MANUFACTURING METHOD AND DEVICE

[CLAIMS]

[CLAIM 1] A wavelength stabilizing control method to maintain a center wavelength of a laser beam oscillated from a laser light source to a predetermined set wavelength, said wavelength stabilizing control method including:

a first step of measuring in advance temperature dependence of a detection reference wavelength of a wavelength detection unit used to detect a wavelength of said laser beam;

a second step of performing an absolute wavelength calibration to make said detection reference wavelength of said wavelength detection unit almost coincide with an absolute wavelength provided from an absolute wavelength provision source, said absolute wavelength close to said set wavelength; and

a third step of setting said detection reference wavelength of said wavelength detection unit to said set wavelength, based on said temperature dependence obtained in said first step.

[CLAIM 2] The wavelength stabilizing control method according to Claim 1, wherein

said wavelength detection unit is a Fabry-Perot etalon, and

in said first step, temperature dependence of a resonance wavelength of said wavelength detection unit is measured;

in said second step, said resonance wavelength is made to almost coincide with said absolute wavelength by controlling temperature of said wavelength detection unit; and

in said third step, said resonance wavelength is set as said set wavelength by controlling temperature of said wavelength detection unit.

[CLAIM 3] The wavelength stabilizing control method according to Claim 2, wherein

said absolute wavelength provision source is an absorption cell on which said laser beam is incident, and

in said second step, absorption of an absorption line closest to said set wavelength of said absorption cell and transmittance of said wavelength detection unit are maximized.

[CLAIM 4] The wavelength stabilizing control method according to any one of Claims 1 to 3, wherein

in said first step, temperature dependence of said center wavelength of said laser beam is further measured in advance; and

in said second step, a wavelength control of said laser beam is performed together.

[CLAIM 5] The wavelength stabilizing control method according to any one of Claims 1 to 4, wherein said method further includes a fourth step of controlling a wavelength of said laser beam from said laser light source, based on detection results of said wavelength detection unit which detection reference wavelength is set to said set wavelength in said third step.

[CLAIM 6] The wavelength stabilizing control method according to one of Claims 4 and 5, wherein said wavelength control of said laser beam is performed, by controlling at least one of a temperature of said laser light source and a current supplied to said laser light source.

[CLAIM 7] A light source unit, said unit comprising:

a laser light source which oscillates a laser beam;

a beam monitor mechanism which monitors the optical properties of said laser beam related to wavelength stabilizing to maintain a center wavelength of said laser beam to a predetermined set wavelength;

a memory unit which stores a temperature dependence map including temperature dependence data of a detection reference wavelength of said beam monitor mechanism;

an absolute wavelength provision source which provides an absolute wavelength close to said set wavelength; and

a first control unit which performs an absolute wavelength calibration to make said detection reference

wavelength of said beam monitor mechanism almost coincide with said absolute wavelength provided by said absolute wavelength provision source, and also a set wavelength calibration to make said detection reference wavelength coincide with said set wavelength based on said temperature dependence map.

[CLAIM 8] The light source unit according to Claim 7, wherein

said beam monitor mechanism includes a Fabry-Perot etalon,

said temperature dependence map includes data based on measurement results on temperature dependence of a resonance wavelength of said Fabry-Perot etalon, and

said first control unit performs said absolute wavelength calibration and said set wavelength calibration on said detection reference wavelength by controlling a temperature of said Fabry-Perot etalon structuring said beam monitor unit.

[CLAIM 9] The light source unit according to Claim 8, wherein

said temperature dependence map further includes data on temperature dependence of a center wavelength of said laser beam oscillated from said laser light source, and

said first control unit performs wavelength control of said laser light source together, when performing said absolute wavelength calibration.

[CLAIM 10] The light source unit according to one of

Claims 8 and 9, wherein

said absolute wavelength provision source is an absorption cell on which said laser beam is incident, and

said first control unit maximizes absorption of an absorption line closest to said set wavelength of said absorption cell, as well as maximizes transmittance of said Fabry-Perot etalon, when performing said absolute wavelength calibration.

[CLAIM 11] The light source unit according to any one of Claims 8 to 10, said light source unit further comprising a fiber amplifier, which amplifies said laser beam from said laser light source.

[CLAIM 12] The light source unit according to Claim 11, said light source unit further comprising a wavelength conversion unit, which includes a nonlinear optical crystal to convert a wavelength of said amplified laser beam.

[CLAIM 13] The light source unit according to any one of Claims 7 to 12, said light source unit further comprising a second control unit which feedback controls a wavelength of said laser beam from said laser light source after said set wavelength calibration is completed, based on monitoring results of said beam monitor mechanism which has completed said set wavelength calibration.

[CLAIM 14] An exposure method which forms a predetermined pattern on a substrate by exposing said

substrate with a laser beam, said exposure method including:

a first step which sequentially performs;

a first sub-step of measuring in advance a temperature dependence of a detection reference wavelength in a wavelength detection unit used to detect a wavelength of said laser beam, prior to starting exposure,

a second sub-step of performing an absolute wavelength calibration to make said detection reference wavelength of said wavelength detection unit almost coincide with an absolute wavelength provided from an absolute wavelength provision source, said absolute wavelength close to a set wavelength, and

a third sub-step of setting said detection reference wavelength of said wavelength detection unit to said set wavelength, based on said temperature dependence obtained in said first sub-step, and after these sub-steps are completed; and

a second step of repeatedly performing exposure on said substrate with said laser beam, while controlling a wavelength of said laser beam from said laser light source based on detection results of said wavelength detection unit which said detection reference wavelength is set at said set wavelength in said third sub-step.

[CLAIM 15] The exposure method according to Claim 14,

wherein

an optical system is further arranged on a path of said laser beam, and said exposure method further includes:

a third step of changing said set wavelength in order to cancel a change in optical performance of said optical system.

[CLAIM 16] An exposure apparatus which illuminates a mask with a laser beam and transfers a pattern of said mask onto a substrate, said exposure apparatus comprising:

a light source unit that has a laser light source oscillating said laser beam, a beam monitor mechanism which monitors optical properties of said laser beam related to wavelength stabilizing in order to maintain a center wavelength of said laser beam at a predetermined set wavelength, and an absolute wavelength provision source which provides an absolute wavelength close to said set wavelength;

a memory unit where a temperature dependence map is stored, said temperature dependence map made up of measurement data on both a center wavelength of said laser beam oscillated from said laser light source and a temperature dependence of a detection reference wavelength of said beam monitor mechanism;

a first control unit which performs an absolute wavelength calibration to make a detection reference

wavelength of said beam monitor mechanism almost coincide with an absolute wavelength provided from said absolute wavelength provision source, and also performs a set wavelength calibration to make said detection reference wavelength coincide with said set wavelength based on said temperature dependence map; and

a second control unit which exposes said substrate via said mask by irradiating said laser beam on said mask, while performing feedback control on a wavelength of a laser beam emitted from said light source unit based on monitoring results of said beam monitor mechanism which has completed said set wavelength calibration.

[CLAIM 17] The exposure apparatus according to Claim 16, said exposure apparatus further comprising:

a projection optical system which projects said laser beam outgoing from said mask onto said substrate;

an environmental sensor which measures a physical quantity related to nearby surroundings of said projection optical system; and

a third control unit which calculates a wavelength change amount to almost cancel out change in image forming characteristics of said projection optical system due to change in said physical quantity from a standard state based on measurement values of said environmental sensor and changes said set wavelength in accordance with said wavelength change amount, each at a predetermined timing after exposure on said substrate by said second

control unit has started.

[CLAIM 18] The exposure apparatus according to Claim 17, said exposure apparatus further comprising:

an image forming characteristics correction unit which corrects image forming characteristics of said projection optical system, and

said image forming characteristics correction unit corrects change in image forming characteristics excluding change in image forming characteristics of said projection optical system corrected by changing said set wavelength, each time when said set wavelength is changed by said third control unit.

[CLAIM 19] The exposure apparatus according to Claim 18, wherein said image forming characteristic correction unit corrects change in said image forming characteristic in consideration of change in said physical quantity, in between said set wavelength changing operation by said third control unit.

[CLAIM 20] The exposure apparatus according to any one of Claims 17 to 19, wherein said environmental sensor detects at least atmospheric pressure.

[CLAIM 21] The exposure apparatus according to any one of Claims 16 to 20, wherein said light source unit further comprises a fiber amplifier, which amplifies said laser beam from said laser light source.

[CLAIM 22] The exposure apparatus according to Claim 21, wherein said light source unit further comprises a

wavelength conversion unit, which includes a nonlinear optical crystal to convert a wavelength of said amplified laser beam.

[CLAIM 23] The exposure apparatus according to Claim 22, wherein said beam monitor mechanism structuring said light source unit monitors optical properties of one of an intermediate harmonic wave halfway through wavelength conversion and a final harmonic wave after wavelength conversion.

[CLAIM 24] The exposure apparatus according to Claim 22, wherein said laser light source is a solid-state laser which oscillates a laser beam having a single wavelength within a range of visible to infrared region, and said wavelength conversion unit converts said laser beam to a laser beam having a wavelength of ultraviolet region.

[CLAIM 25] A device manufacturing method including a lithographic process, wherein said exposure method according to one of Claims 14 and 15 is used in said lithographic process.

[CLAIM 26] A device manufacturing method including a lithographic process, wherein exposure is performed using said exposure apparatus according to any one of Claims 16 to 24 in said lithographic process.

[CLAIM 27] A device manufactured using said device manufacturing method according to one of Claims 25 and 26.

[CLAIM 28] An exposure apparatus that exposes a

substrate coated with a photosensitive agent with an energy beam, said exposure apparatus comprising:

a beam source which generates said energy beam;

a wavelength changing unit which changes a wavelength of said energy beam emitted from said beam source; and

an exposure amount control unit which controls an exposure amount provided to said substrate in accordance with an amount of change in sensitivity properties of said photosensitive agent due to a change in wavelength, when said wavelength is changed by said wavelength changing unit.

[DETAILED DESCRIPTION OF THE INVENTION]

[0001]

[RELEVANT TECHNICAL FIELD TO THE INVENTION]

The present invention relates to a wavelength stabilizing control method and a light source unit, an exposure method and an exposure apparatus, and device manufacturing method and a device. More particularly, the present invention relates to a wavelength stabilizing control method to maintain the center wavelength of a laser beam at a predetermined set wavelength and a light source unit to which the method is applied, an exposure method and an exposure apparatus in which exposure is performed using the leaser beam whose wavelength is stabilized by said method, and a method in which a device is manufactured using the exposure apparatus and exposure method and a device manufactured in the device

manufacturing method.

[0002]

[RELATED ART]

Conventionally, in the lithographic process to manufacture a semiconductor device (integrated circuit), a liquid crystal display device, and the like, various exposure apparatus were used. In recent years, as these types of exposure apparatus, the reduction projection exposure apparatus such as the so-called stepper or the so-called scanning stepper is mainstream, from the viewpoint of having high throughput. With the reduction projection exposure apparatus, a fine circuit pattern formed on a photomask or a reticle is reduced, projected, and transferred onto a substrate such as a wafer or a glass plate, which surface is coated with a photoresist via a projection optical system.

[0003]

However, the exposure apparatus such as the projection exposure apparatus require high resolution, along with high throughput. The resolution R, and the depth of focus DOF of the projection exposure apparatus are respectively expressed in the following equation (1) and (2), using the wavelength of the illumination light for exposure λ and the numerical aperture of the projection optical system N.A.:

[0004]

$$R = K \cdot \lambda \;/\; N.A. \qquad \cdots\cdots (1)$$

[0005]

$DF = \lambda / 2 (N.A.)^2$ ······(2)

[0006]

As is obvious from equation (1), three ways can be considered to obtain a smaller resolution R, that is, to decrease the minimum pattern line width that can be resolved; ① reduce the proportional constant K, ② increase the N.A., ③ reduce the wavelength of the illumination light for exposure λ. The proportional constant K, in this case, is a constant that is determined by the projection optical system or the process, and is normally a value around 0.5 to 0.8. The method of decreasing the constant K is called super-resolution in a broad sense. Up until now, issues such as improvement of the projection optical system, modified illumination, phase shift reticle have been studied and proposed, however, there were drawbacks such as the patterns suitable for application being restricted.

[0007]

On the other hand, as can be seen from equation (1), the resolution R can be reduced by increasing the numerical aperture N.A., however, at the same time, this means that the depth of focus DOF is small, as is obvious from equation (2). Therefore, increasing the N.A. value has its limits, and normally, the appropriate value is around 0.5 to 0.6.

[0008]

Accordingly, the most simple and effective way of reducing the resolution R is to reduce the wavelength of

the illumination light for exposure λ.

[0009]

For such reasons, conventionally, the g-line stepper and the i-line stepper that use an ultra-high pressure mercury lamp as the light source for exposure to emit the emission line (such as the g line or the i line) in the ultraviolet light region were mainly used, as the stepper or the like. However, in recent years, the KrF excimer laser stepper that uses a KrF excimer laser as the light source to emit a KrF excimer laser beam having a shorter wavelength (wavelength: 248nm) is becoming mainstream. And currently, the exposure apparatus that uses the ArF excimer laser (wavelength: 193nm) as the light source having a shorter wavelength is under development.

[0010]

As is well known, in the case of using an excimer laser beam in the short wavelength region, mainly due to the transmittance of the material, the material that can be used for the lens of the projection optical system at this stage is limited to materials such as synthetic quartz, fluorite, or fluoride crystal such as lithium fluoride.

[0011]

In the case of using lenses made of materials such as quartz or fluorite in the projection optical system, however, correction of chromatic aberration is actually difficult. Therefore, in order to prevent the image forming performance from deteriorating, narrowing the

oscillation spectral width of the excimer laser beam, in other words, to narrow-band the wavelength is required. To perform this narrow-banding, for example, a narrow-band module (optical elements such as a combination of a prism and a grating (diffraction grating) or an etalon) arranged in a laser resonator is used, and it becomes necessary to keep the spectrum width of the wavelength of the excimer laser beam supplied to the projection optical system during exposure within a predetermined wavelength width at all times, and at the same time, the so-called wavelength stabilizing control to maintain the center wavelength at a predetermined wavelength becomes required.

[0012]

In order to achieve the wavelength stabilizing control referred to above, the optical properties of the excimer laser beam (such as the center wavelength and the spectral half-width) need to be monitored. The wavelength monitor portion of the excimer laser unit is made up of a Fabry-Perot etalon (hereinafter also referred to as an "etalon element") playing the main role, which is in general a Fabry-Perot spectroscope.

[0013]

[PROBLEMS TO BE SOLVED BY THE INVENTION]

The excimer laser, however, has disadvantages as the light source for the exposure apparatus, such as, the size being large, the energy per pulse being large causing the optical components to damage easily, and the maintenance of the laser being complicated and expensive

because of using poisonous fluorine gas.

[0014]

In addition, with higher integration of the semiconductor device, the pattern line width is becoming finer, and further improvement on exposure accuracy such as the overlay accuracy of the mask and the substrate in the exposure apparatus such as the stepper is being required. The overlay accuracy depends on how well the aberration of distortion components and the like in the projection optical system is suppressed. Therefore, the center wavelength stability of the illumination light for exposure and further narrow-banding are becoming required in the exposure apparatus. Of these requirements, as a method of coping with narrow-banding, employing a single-wavelength light source as the laser light source itself can be considered.

[0015]

Meanwhile, since the projection optical system is adjusted only to a predetermined exposure wavelength, if the center wavelength cannot be stably maintained, as a consequence, chromatic aberration of the projection optical system may occur, or the magnification of the projection optical system or the image forming characteristics such as distortion and focus may vary. Therefore, it is a mandatory to maintain the stability of the center wavelength.

[0016]

However, since the etalon element is affected by the

temperature and pressure of the etalon atmosphere, the influence of the change in temperature and atmospheric pressure in the etalon atmosphere cannot be ignored.

[0017]

In addition, it is certain that a finer device rule (the practical minimum line width) will be required in the future, and the exposure apparatus of the next generation will require higher overlay accuracy than before. The overly accuracy depends, for example, on how well the distortion component is suppressed. Also, in order to increase the depth of focus, increase in the UDOF (usable DOF) and stability in focus will be necessary. And in both cases, stability of the center wavelength and controllability of the spectral half-width are required at a high degree.

[0018]

The present invention has been made in consideration of the situation described above, and has as its first object to provide a wavelength stabilizing control method that can maintain the center wavelength of the laser beam at a predetermined set wavelength without fail, and a light source unit.

[0019]

It is the second object of the present invention to provide an exposure method and an exposure apparatus in which exposure with high precision can be performed without being affected by the temperature change and the like in the atmosphere.

[0020]

It is the third object of the present invention to provide a device manufacturing method that can improve the productivity of the microdevice with high integration.

[0021]

It is the fourth object of the present invention to provide an exposure apparatus that can perform exposure with sufficient accuracy regardless of the change in sensitivity properties of the photosensitive agent.

[0022]

[MEANS FOR SOLVING THE PROBLEMS]

The invention according to Claim 1 is a wavelength stabilizing control method to maintain a center wavelength of a laser beam oscillated from a laser light source (160A) to a predetermined set wavelength, the wavelength stabilizing control method including: a first step of measuring in advance temperature dependence of a detection reference wavelength of a wavelength detection unit (164) used to detect a wavelength of the laser beam; a second step of performing an absolute wavelength calibration to make the detection reference wavelength of the wavelength detection unit almost coincide with an absolute wavelength provided from an absolute wavelength provision source (165), the absolute wavelength close to the set wavelength; and a third step of setting the detection reference wavelength of the wavelength detection unit to the set wavelength, based on the temperature dependence obtained in the first step.

[0023]

The concept "the absolute wavelength close to the set wavelength," here, includes the wavelength of the absolute wavelength being the same as the set wavelength.

[0024]

With this method, in the first step, the temperature dependence of the detection reference wavelength of the wavelength detection unit used to detect the wavelength of the laser beam is measured in advance. Then, in the second step, an absolute wavelength calibration is performed to make the detection reference wavelength of the wavelength detection unit almost coincide with the absolute wavelength close to the set wavelength, provided from an absolute wavelength provision source. And, in the third step, the detection reference wavelength of the wavelength detection unit is set to the set wavelength, based on the temperature dependence obtained in the first step. In this manner, according to the present invention, since the temperature dependence of the detection reference wavelength of the wavelength detection unit measured in advance is used to set the detection reference wavelength of the wavelength detection unit that has completed the absolute wavelength calibration to the set wavelength, the detection reference wavelength of the wavelength detection unit can be accurately set to the set wavelength without fail at all times. So, even if the atmosphere of the wavelength detection unit such as the temperature changes, a wavelength stabilizing control

which securely maintains the center wavelength of the laser beam at a predetermined set wavelength using the wavelength detection unit becomes possible, without being affected by the change.

[0025]

In this case, as in the invention according to Claim 2, when the wavelength detection unit is a Fabry-Perot etalon, in the first step, temperature dependence of a resonance wavelength of the wavelength detection unit may be measured; in the second step, the resonance wavelength may be made to almost coincide with the absolute wavelength by controlling temperature of the wavelength detection unit; and in the third step, the resonance wavelength may be set as the set wavelength by controlling temperature of the wavelength detection unit. In such a case, by utilizing the temperature dependence of the resonance wavelength, which is the reference for wavelength detection of the Fabry-Perot etalon, it becomes possible to set the resonance wavelength (detection reference wavelength) to the set wavelength.

[0026]

In this case, as in the invention according to Claim 3, when the absolute wavelength provision source is an absorption cell on which the laser beam is incident, in the second step, absorption of an absorption line closest to the set wavelength of the absorption cell and transmittance of the wavelength detection unit may be maximized.

[0027]

In the "an absorption line closest to the set wavelength," the "absorption line that has the same wavelength as the set wavelength," is also included.

[0028]

In each invention according to Claims 1 to 3, as in the invention according to Claim 4, in the first step, temperature dependence of the center wavelength of the laser beam may be further measured in advance; and in the second step, a wavelength control of the laser beam may be performed together. In such a case, the absolute wavelength calibration referred to earlier can be completed within a shorter period of time compared with the case when the wavelength control of the laser beam is not performed.

[0029]

In each invention according to Claims 1 to 4, as in the invention according to Claim 5, the method may further include a fourth step of controlling a wavelength of the laser beam from the laser light source, based on detection results of the wavelength detection unit which detection reference wavelength is set to the set wavelength in the third step. In such a case, the wavelength of the laser beam from the laser light source is controlled based on the detection results of wavelength detection unit which detection reference wavelength is accurately set to the set wavelength. Thus, the wavelength of the laser beam can be stably maintained

at the set wavelength.

[0030]

In each invention according to Claims 4 and 5, as in the invention according to Claim 6, the wavelength control of the laser beam may be performed, by controlling at least one of a temperature and a current supplied to the laser light source. For example, in the case of a single wavelength oscillation laser such as the DFB semiconductor laser or the fiber laser the oscillation wavelength of the laser can be controlled by temperature control, or in the case of the DFB semiconductor laser the oscillation wavelength of the laser can also be controlled by controlling the supply current (drive current).

[0031]

A light source unit related to the invention according to Claim 7 comprises: a laser light source (160A) which oscillates a laser beam; a beam monitor mechanism (164) which monitors the optical properties of the laser beam related to wavelength stabilizing to maintain a center wavelength of the laser beam to a predetermined set wavelength; a memory unit (51) which stores a temperature dependence map including temperature dependence data of a detection reference wavelength of the beam monitor mechanism; an absolute wavelength provision source which provides an absolute wavelength close to the set wavelength; and a first control unit (50) which performs an absolute wavelength calibration to

make the detection reference wavelength of the beam monitor mechanism almost coincide with the absolute wavelength provided from the absolute wavelength provision source (165), and also performs a set wavelength calibration to make the detection reference wavelength coincide with the set wavelength based on the temperature dependence map.

[0032]

"An absolute wavelength close to the set wavelength" here includes the concept of the absolute wavelength being the same wavelength as the set wavelength.

[0033]

With the light source unit, the temperature dependence map including temperature dependence data of the detection reference wavelength of the beam monitor mechanism is stored in the memory unit. And, the first control unit performs an absolute wavelength calibration in order to make the detection reference wavelength of the beam monitor mechanism almost coincide with the absolute wavelength provided by the absolute wavelength provision source, as well as performs a set wavelength calibration to make the detection reference wavelength coincide with the set wavelength, based on the temperature dependence map. In this manner, according to the present invention, the set wavelength calibration is performed to make the set wavelength coincide with the detection reference wavelength of the beam monitor mechanism on which the absolute wavelength calibration

has been performed, using the temperature dependence map including the temperature dependence data of the detection reference wavelength of the beam monitor mechanism already known. Therefore, the detection reference wavelength of the beam monitor mechanism can be accurately set to the set wavelength at all times without fail, and as a consequence, a wavelength stabilizing control which securely maintains the center wavelength of the laser beam at a predetermined set wavelength using the beam monitor mechanism becomes possible, without being affected by changes in the atmosphere of the beam monitor mechanism, such as the temperature.

[0034]

In this case, as in the invention according to Claim 8, when the beam monitor mechanism includes a Fabry-Perot etalon, and the temperature dependence map includes data based on measurement results on temperature dependence of the resonance wavelength of the Fabry-Perot etalon, the first control unit may perform the absolute wavelength calibration and the set wavelength calibration on the detection reference wavelength by controlling the temperature of the Fabry-Perot etalon structuring the beam monitor unit. In such a case, it becomes possible to set the detection reference wavelength to the set wavelength utilizing the temperature dependence of the resonance wavelength, which is the base of the wavelength detection of the Fabry-Perot etalon.

[0035]

In this case, as in the invention according to Claim 9, when the temperature dependence map may further include data on temperature dependence of the center wavelength of the laser beam oscillated from the laser light source, the first control unit may perform wavelength control of the laser light source together, when performing the absolute wavelength calibration. In such a case, the absolute wavelength calibration can be completed within a shorter period of time compared with the case when wavelength control of the laser beam is not performed.

[0036]

In each invention according to Claims 8 and 9, as in the invention according to Claim 10, the absolute wavelength provision source may be an absorption cell (165) on which the laser beam is incident, and the first control unit may maximize absorption of an absorption line closest to the set wavelength of the absorption cell, as well as maximize transmittance of the Fabry-Perot etalon, when performing the absolute wavelength calibration.

[0037]

"An absorption line closest to the set wavelength," here, includes "an absorption line that has the same wavelength as the set wavelength".

[0038]

In each invention according to Claims 8 to 10, as in the invention according to Claim 11, the light source

unit may further comprise a fiber amplifier (168_n, 171_n) which amplifies the laser beam from the laser light source. In such a case, since the fiber amplifier can amplify the laser beam from the laser light source, even if the required light amount is large, it becomes possible to use a compact type laser light source, for example, a solid-state laser such as the DFB semiconductor laser or the fiber laser. Thus, the light source unit can be made compact and lightweight.

[0039]

In this case, as in the invention according to Claim 12, the light source unit may further comprise a wavelength conversion unit (163) which includes a nonlinear optical crystal to convert a wavelength of the amplified laser beam. In such a case, it becomes possible to convert the wavelength of the amplified laser beam with the wavelength conversion unit. So, for example, by generating a harmonic wave by converting the wavelength of the laser beam with the wavelength conversion unit, a compact light source, which emits a high power energy beam having a short wavelength, can be realized.

[0040]

In the light source unit related to each invention according to Claims 7 to 12, as in the invention according to Claim 13, the light source unit may further comprise a second control unit (50) which feedback controls a wavelength of the laser beam from the laser light source after the set wavelength calibration is

completed, based on monitoring results of the beam monitor mechanism which has completed the set wavelength calibration. In such a case, the second control unit controls the wavelength of the laser beam emitted from the laser light source based on the monitoring results of the beam monitor mechanism which detection reference wavelength is accurately set to the set wavelength. Therefore, the wavelength of the laser beam can be stably maintained at the set wavelength.

[0041]

The invention according to Claim 14 is an exposure method which forms a predetermined pattern on a substrate by exposing the substrate with a laser beam, the exposure method including: a first step which sequentially performs; a first sub-step of measuring in advance a temperature dependence of a detection reference wavelength in a wavelength detection unit (164) used to detect a wavelength of the laser beam, prior to starting exposure, a second sub-step of performing absolute wavelength calibration to make the detection reference wavelength of the wavelength detection unit almost coincide with an absolute wavelength provided from an absolute wavelength provision source (165) that provides the absolute wavelength close to a set wavelength, and a third sub-step of setting the detection reference wavelength of the wavelength detection unit to the set wavelength, based on the temperature dependence obtained in the first sub-step, and after these sub-steps are

completed, a second step of repeatedly performing exposure on the substrate with the laser beam, while controlling a wavelength of the laser beam from the laser light source based on detection results of the wavelength detection unit which the detection reference wavelength is set at the set wavelength in the third sub-step.

[0042]

With the exposure method, by the process in the first step, the detection reference wavelength of the wavelength detection unit that has completed absolute wavelength calibration is set to the set wavelength using the temperature dependence of the detection reference wavelength of the wavelength detection unit, which is measured in advance. Therefore, the detection reference wavelength of the wavelength detection unit is accurately set to the set wavelength without fail at all times. And, in the second step, the substrate is repeatedly exposed with the laser beam, while the wavelength of the laser beam emitted from the laser light source is controlled based on the detection results of the wavelength detection unit which detection reference wavelength is set to the set wavelength. Accordingly, with the present invention, even if the atmosphere of the wavelength detection unit such as the temperature changes, the detection reference wavelength of the wavelength detection unit can be accurately set to the set wavelength without being affected by the change, and the substrate is repeatedly exposed with the laser beam while

the wavelength stabilizing control is preformed to securely maintain the center wavelength of the laser beam at a predetermined set wavelength using the wavelength detection unit. Thus, exposure with high precision that is hardly affected by temperature changes and the like in the atmosphere becomes possible.

[0043]

In this case, as in the invention according to Claim 15, when an optical system (12, PL) is further arranged on a path of the laser beam, the exposure method may further include: a third step of changing the set wavelength in order to cancel a change in optical performance of the optical system. For example, when there is change in the atmospheric pressure, the optical performance of the optical system (such as various aberrations) may change. In such a case, in the third step, since the set wavelength is changed in order to cancel the change in the optical performance of the optical system, the substrate can be repeatedly exposed with the laser beam while performing the wavelength stabilizing control to securely maintain the center wavelength of the laser beam at a predetermined set wavelength using the changed set wavelength as a reference and using the wavelength detection unit. Therefore, as a consequence, exposure with favorable accuracy is performed in a state as if there were no atmospheric pressure change (that is, a state where the amount of change in the optical performance is cancelled

out).

[0044]

The invention according to Claim 16 is an exposure apparatus which illuminates a mask (R) with a laser beam and transfers a pattern of the mask onto a substrate (W), the exposure apparatus comprising: a light source unit (16) that has a laser light source (160A) oscillating the laser beam, a beam monitor mechanism (164) which monitors optical properties of the laser beam related to wavelength stabilizing in order to maintain the center wavelength of the laser beam at a predetermined set wavelength, and an absolute wavelength provision source (165) which provides an absolute wavelength close to the set wavelength; a memory unit (51) where a temperature dependence map is stored, the temperature dependence map made up of measurement data on both a center wavelength of the laser beam oscillated from the laser light source and a temperature dependence of a detection reference wavelength of the beam monitor mechanism; a first control unit (50) which performs an absolute wavelength calibration to make a detection reference wavelength of the beam monitor mechanism almost coincide with an absolute wavelength provided from the absolute wavelength provision source, and also performs a set wavelength calibration to make the detection reference wavelength coincide with the set wavelength based on the temperature dependence map; and a second control unit (50) which exposes the substrate via the mask by irradiating the

laser beam on the mask, while performing feedback control on a wavelength of a laser beam emitted from the light source unit based on monitoring results of the beam monitor mechanism which has completed the set wavelength calibration.

[0045]

With this exposure apparatus, the absolute wavelength calibration and the set wave calibration is performed by the first control unit, to make the detection wavelength of the beam monitor mechanism almost coincide with the absolute wavelength provided from the absolute wavelength provision source, and to make the detection reference wavelength coincide with the set wavelength based on the temperature dependence map (which is made up of measurement data on the center wavelength of the laser beam oscillated from the laser light source and the temperature dependence of the detection reference wavelength of the beam monitor mechanism) stored in the memory unit. In this manner, by utilizing the temperature dependence of the detection reference wavelength of the beam monitor mechanism already known, the detection reference wavelength of the beam monitor mechanism that has completed absolute wavelength calibration, can be made to coincide with the set wavelength. And, the second control unit feedback controls the wavelength of the laser beam emitted from the light source unit, based on the monitoring results of the beam monitor mechanism that has completed the set wavelength calibration, while

performing exposure on the substrate via the mask by irradiating the laser beam on the mask. Accordingly, based on the monitoring results of the beam monitor mechanism, a wavelength stabilizing control, which securely maintains the center wavelength of the laser beam at a predetermined set wavelength, can be performed, while irradiating the laser beam on the mask to expose the substrate via mask. Thus, exposure with high precision, which is hardly affected by the change in the atmosphere such as the temperature, can be achieved.

[0046]

In this case, as in the invention according to Claim 17, when the exposure apparatus further comprises: a projection optical system (PL) which projects the laser beam outgoing from the mask onto the substrate; and an environmental sensor (77) which measures a physical quantity related to nearby surroundings of the projection optical system; the exposure apparatus may further comprise a third control unit (50) which calculates a wavelength change amount to almost cancel out change in image forming characteristics of the projection optical system due to change in the physical quantity from a standard state based on measurement values of the environmental sensor and changes the set wavelength in accordance with the wavelength change amount, each at a predetermined timing after exposure on the substrate by the second control unit has started. When the physical quantity (such as the pressure, temperature, and humidity

of the surrounding gas) related to the environment in which the projection optical system is arranged changes from the standard state, the refractive index of the atmosphere changes. And due to this change, the exposure wavelength of the projection optical system originally adjusted to the standard state (the set wavelength) changes, however, if the laser beam which wavelength is in the original state is irradiated on the projection optical system as the exposure light, various aberration (including chromatic aberration) occur due to the change in physical quantity of the image forming characteristics of the projection optical system. With the present invention, in such a case, each at a predetermined timing after exposure on the substrate has started, the third control unit calculates the wavelength change amount to almost cancel out the change in the image forming characteristics of the projection optical system due to the change in the physical quantity from the standard state, based on measurement values of the environmental sensor; and also changes the set wavelength in accordance with the wavelength change amount. As a consequence, various aberrations of the projection optical system are corrected at the same time, and the second control unit irradiates the laser beam onto the mask, while using the changed set wavelength as a reference to perform wavelength stabilizing control with the beam monitor mechanism so as to maintain the center wavelength of the laser beam at a predetermined set wavelength without fail.

Thus, the laser beam outgoing from the mask is projected onto the substrate by the projection optical system, and the substrate is exposed. In this case, exposure is performed with favorable accuracy, as if there were no change in the physical quantity related to the environment (that is, a state where the change amount in the image forming characteristics is cancelled out).

[0047]

For example, if the physical quantity includes the atmospheric pressure, the atmospheric pressure in the standard state (standard atmospheric pressure) may be arbitrary, however, it is preferable for the atmospheric pressure to be the reference when performing adjustment on the projection optical system and the like so as to maximize the optical performance (including the image forming characteristics). In this case, the change amount in the optical performance of the projection optical system and the like under the standard atmospheric pressure is zero. The standard atmospheric pressure, normally, is often set at the average atmospheric pressure of the delivery place (such as factories) where the exposure apparatus is arranged. Accordingly, when there is an altitude difference between the places where the exposure apparatus is built and where the exposure apparatus will be arranged (delivered), for example, adjustment of the projection optical system and the like are performed at the place where the exposure apparatus is built by shifting the exposure wavelength by only the

amount corresponding to the altitude difference as if the projection optical system were arranged under the standard atmospheric pressure (average atmospheric pressure), and adjusting the wavelength back to the exposure wavelength at the place where the exposure apparatus will be arranged. Or the adjustment of the projection optical system is performed at the place where the exposure apparatus is built with the exposure wavelength, and the exposure wavelength is shifted at the place where the exposure apparatus will be arranged so as to cancel out the altitude difference.

[0048]

In the case the projection optical system is arranged in a gaseous environment other than air, the "atmospheric pressure" referred to above is to be the pressure of the gas surrounding the projection optical system.

[0049]

The present invention utilizes the fact that changing the wavelength of the illumination light with the projection optical system and changing the set environment (the pressure, temperature, humidity and the like of the surrounding gas) of the projection optical system are substantially equivalent. When the refraction element of the projection optical system is made of a single material, then the equivalence is complete, and in the case a plurality of materials are used, the equivalence is almost complete. Accordingly, by using the variation characteristics of the refractive index of the

projection optical system (especially the refraction element) in respect to the set environment and changing only the wavelength of the illumination light, an equivalent state of when the set environment of the projection optical system has been changed can be substantially created.

[0050]

The predetermined timing, here, may be each time when exposure on predetermined slices of substrates has been completed, or may be each time when exposure on each shot area on the substrate has been completed, or may be each time when the exposure conditions are changed. The predetermined slices may be one, or it may be the slices of wafers equivalent to one lot. In addition, changes in exposure conditions include all changes related to exposure in a broad sense, such as when the mask is exchanged, besides changes in illumination conditions.

[0051]

Or, the predetermined timing may be the timing when the change in physical quantity (or the change amount) related to the environment obtained based on the measurement values of the environmental sensor exceeds a predetermined amount, or the predetermined timing may be almost realtime, corresponding to the interval calculating the optical performance (or the fluctuation amount) of the projection optical system (for example, several μs). Or, the predetermined timing may be every predetermined timing set in advance.

[0052]

In this case, as in the invention according to Claim 18, the exposure apparatus may further comprise: an image forming characteristics correction unit (50, 74a, 74b, 74c, 78) which corrects image forming characteristics of the projection optical system, and the image forming characteristics correction unit may correct change in image forming characteristics excluding change in image forming characteristics of the projection optical system corrected by changing the set wavelength, each time when the set wavelength is changed by the third control unit.

[0053]

The "change in image forming characteristics excluding change in image forming characteristics of the projection optical system corrected by changing the set wavelength," includes the change in the image forming characteristics due to the fluctuation in physical quantity which was not corrected by the change of the set wavelength, when the change in image forming characteristics of the projection optical system due to the fluctuation in physical quantity could not be corrected completely by the change of set wavelength.

[0054]

In such a case, most of the change in the image forming characteristics of the projection optical system due to the fluctuation in physical quantity (hereinafter referred to as the "environmental change" as appropriate) is corrected by the change in set wavelength mentioned

above, and the remaining environmental change is corrected by the image forming characteristics correction unit along with other changes such as the irradiation change. As a result, exposure with high precision is performed in a state where the image forming characteristics of the projection optical system is almost completely corrected.

[0055]

In this case, as in the invention according to Claim 19, in between the set wavelength changing operation by the third control unit, the image forming characteristics correction unit may correct the change in image forming characteristics in consideration of the change in wavelength of the laser beam. The change in set wavelength is performed in the predetermined timing stated above. When the interval between the changes is long, however, the physical quantity is likely to change, therefore, the image forming characteristics correction unit corrects the environmental change occurring due to this change.

[0056]

In the exposure apparatus according to Claims 17 to 19, as in the invention according to Claim 20, the environmental sensor may at least detect the atmospheric pressure.

[0057]

In the exposure apparatus related to each invention according to Claims 16 to 20, as in the invention

according to Claim 21, the light source unit (16) may further comprise a fiber amplifier (168_n, 171_n) which amplifies the laser beam from the laser light source. In such a case, since the fiber amplifier amplifies the laser beam emitted from the laser light source, even if the required light amount is large, a compact laser light source, for example, a solid-state laser such as the DFB semiconductor laser or the fiber laser can be used, and a light source unit of a smaller and lighter size can be realized, which leads to a smaller footprint of the exposure apparatus.

[0058]

In this case, as in the invention according to Claim 22, the light source unit may further comprise a wavelength conversion unit (163) which includes a nonlinear optical crystal to convert a wavelength of the amplified laser beam. In such a case, it becomes possible to convert the wavelength of the amplified laser beam with the wavelength conversion unit. So, for example, by generating a harmonic wave by converting the wavelength of the laser beam with the wavelength conversion unit, emission of a high power energy beam having a short wavelength can be realized. Therefore, resolution of exposure can be improved and a fine pattern can be transferred onto a substrate with high accuracy.

[0059]

In this case, as in the invention according to Claim 23, the beam monitor mechanisms making up the light

source unit may monitor optical properties of either one of an intermediate harmonic wave halfway through wavelength conversion and a final harmonic wave after wavelength conversion, or both of them.

[0060]

In the exposure apparatus related to the invention according to Claim 22, as in the invention according to Claim 24, the laser light source is a solid-state laser which oscillates a laser beam having a single wavelength within a range of visible to infrared regions, and the wavelength conversion unit may convert the laser beam to a laser beam having a wavelength of ultraviolet region. In such a case, exposure can be performed with good resolution by using an ultraviolet light having a shorter wavelength.

[0061]

The invention according to Claim 24 is a device manufacturing method including a lithographic process, and in the lithographic process the exposure method according to one of Claims 14 and 15 is used. In addition, the invention according to Claim 25 is a device manufacturing method including a lithographic process, and in the lithographic process exposure is performed using the exposure apparatus according to any one of Claims 16 to 23.

[0062]

In these device manufacturing methods, a pattern can be transferred onto a substrate with good precision in

each exposure method according of Claims 14 and 15, and by each exposure apparatus according to Claims 16 to 23, and as a consequence, productivity of a microdevice with higher integration can be improved.

[0063]

The invention according to Claim 28 is an exposure apparatus that exposes a substrate (W) coated with a photosensitive agent with an energy beam, the exposure apparatus comprising: a beam source (16A) which generates the energy beam; a wavelength changing unit (16B, 50) which changes a wavelength of the energy beam emitted from the beam source; and an exposure amount control unit (50) which controls an exposure amount provided to the substrate in accordance with an amount of change in sensitivity properties of the photosensitive agent due to a change in wavelength, when the wavelength is changed by the wavelength changing unit.

[0064]

With the exposure apparatus, when the wavelength of the energy beam emitted from the beam source is changed by the wavelength changing unit, the exposure amount provided to the substrate is controlled by the exposure amount control unit in accordance with the amount of change in sensitivity properties of the photosensitive agent due to the wavelength change.

[0065]

That is, when the wavelength of the energy beam is changed, the sensitivity properties of the photosensitive

agent (resist) coated on the substrate may change due to the wavelength change (wavelength shift). In such a case, with the present invention, the exposure amount provided to the substrate can be controlled in accordance with the amount of change in sensitivity properties of the photosensitive agent due to the wavelength change. Accordingly, exposure with good accuracy becomes possible without being affected by the change in sensitivity properties of the photosensitive agent.

[0066]

[EMBODIMENT OF THE INVENTION]

An embodiment of the present invention will be described below with reference to Figs. 1 to 6.

[0067]

Fig. 1 shows the schematic view of the exposure apparatus 10 related to the embodiment, which structure includes the light source unit related to the present invention. The exposure apparatus 10 is a scanning type exposure apparatus based on the step-and-scan method.

[0068]

The exposure apparatus 10 comprises: an illumination system consisting of a light source unit 16 and an illumination optical system 12; a reticle stage RST that holds a reticle R serving as a mask which is illuminated by the illumination light for exposure (hereinafter referred to as "exposure light") IL from the illumination system; a projection optical system PL which projects the exposure light IL outgoing from the reticle R onto a

wafer W serving as a substrate; an XY stage 14 on which a Z tilt stage 58 serving as a substrate stage holding the wafer W is mounted; control systems for these parts; and the like.

[0069]

The light source unit 16 is, for example, a harmonic generation unit that emits an ultraviolet pulse light having a wavelength of 193nm (almost the same wavelength as of the ArF excimer laser beam) or an ultraviolet pulse light having a wavelength of 157nm (almost the same wavelength as of the F_2 laser beam). The light source unit 16 comprises: a light source portion 16A including a laser light source serving as a light source; a laser controller 16B; and a light amount controller 16C. The light source unit 16 is housed within an environmental chamber (hereinafter referred to as "chamber") 11 where the temperature, pressure, humidity, and the like are adjusted with high precision. In the environmental chamber 11, the illumination optical system 12, the reticle stage RST, the projection optical system PL, the Z tilt stage 58, the XY stage 14, and a main body of the exposure apparatus consisting of a main column (not shown in Figs.) on which these parts are arranged, are also housed.

[0070]

Fig. 2 is a block diagram showing the internal structure of the light source unit 16 along with the main controller 50, which performs overall control over the

entire exposure apparatus.

[0071]

As is shown in Fig. 2, the light source portion 16A has a structure including a pulse light generation portion 160 serving as a light generation portion, a light amplifying portion 161, a quarter-wave plate 162, a wavelength conversion portion 163, a beam monitor mechanism 164, an absorption cell 165, and the like.

[0072]

The pulse light generation portion 160 has a laser light source 160A, photocoupler BS1 and BS2, optical isolator 160B, an electro-optic modulator (hereinafter referred to as "EOM") 160C serving as an optical modulator, and the like. And, each element arranged in between the laser light source 160A and the wavelength conversion portion 163 is optically connected to one another by optical fiber.

[0073]

More specifically, as the laser light source 160A, in this case, a single wavelength oscillation laser is used, for example, an InGaAsP DFB semiconductor laser, which has an oscillation wavelength of 1.544μm, continuous-wave output (hereinafter referred to as "CW output") of 20mW, is used. Hereinafter in this description, the laser light source 160A will be referred to as "DFB semiconductor laser 160A", as appropriate.

[0074]

DFB semiconductor laser, in this description, is a

diffraction grating made within the semiconductor laser, instead of the Fabry-Perot resonator having low longitudinal mode selectivity, and is structured to oscillate a single longitudinal mode in any circumstances. It is called the distributed feedback (DFB) laser, and since this type of laser basically performs a single longitudinal mode oscillation, the oscillation spectral line width can be suppressed so that it does not exceed 0.01pm.

[0075]

In addition, the DFB semiconductor laser is usually arranged on a heatsink, and these are housed in a casing. With the embodiment, a temperature adjustment unit (for example, a Peltier element) is arranged on the heatsink of the DFB semiconductor laser 160A, and as will be described later on, the embodiment has a structure so that the laser controller 16B is capable of controlling (adjusting) the oscillation wavelength by controlling the temperature of the temperature adjustment unit.

[0076]

To control the oscillation wavelength as is described above, in the embodiment the temperature dependence of the oscillation wavelength of the DFB semiconductor laser 160A is measured in advance. The measurement results are stored as a temperature dependence map in the form of a table, a conversion function, or a conversion coefficient in the memory 51 serving as a storage unit, which is arranged along with the main controller 50.

[0077]

In the embodiment, the temperature dependence of the oscillation wavelength of the DFB semiconductor laser 160A is around 0.1nm/°C. Accordingly, if the temperature of the DFB semiconductor laser changes 1°C, the wavelength of the reference wave (1544nm) changes 0.1nm. So, in the case of an eighth-harmonic wave (193nm) the wavelength changes 0.0125nm, and in the case of a tenth-harmonic wave (157nm) the wavelength changes 0.01nm.

[0078]

With the exposure apparatus, it is sufficient enough if the wavelength of the illumination light for exposure (pulse light) varies around ±20pm in respect to the center wavelength. Accordingly, in the case of the eighth-harmonic wave the temperature of the DFB semiconductor laser 11 needs to vary around ±1.6°C, and in the case of the tenth-harmonic wave the temperature needs to vary around ±2°C.

[0079]

The laser light source 160A is not limited to semiconductor lasers such as the DFB semiconductor laser. For example, the ytteribium (Yb) doped fiber laser which has an oscillation wavelength of around 990nm can be used.

[0080]

The photocoupler BS1 and BS2 have a transmittance of around 97%. Therefore, the laser beam from the DFB semiconductor laser 160A is separated at the photocoupler BS1, and around 97% of the separated beam is incident on

the photocoupler BS2, whereas, the remaining 3% is incident on the beam monitor mechanism 164. Furthermore, the laser beam incident on the photocoupler BS2 is separated, and around 97% of the separated beam proceeds to the optical isolator 160B, whereas, the remaining 3% is incident on the absorption cell 165.

[0081]

The beam monitor mechanism 164, the absorption cell 165, and the like will be described in detail later on in the description.

[0082]

The optical isolator 160B is a device, which allows only light proceeding from the photocoupler BS2 to the EOM160C to pass, and prevents light proceeding in the opposite direction from passing. The optical isolator 160B prevents the oscillation mode of the DFB semiconductor laser 160A from changing or noise from being generated, which are caused by the reflecting light (returning light).

[0083]

The EOM160C is a device, which converts the laser beam (CW beam (continuous-wave beam) that has passed through the optical isolator 160B into a pulse light. As the EOM160C, an electrooptical modulator (for example, a double-electrode modulator) that has an electrode structure having performed chirp correction is used, so that the wavelength broadening of the semiconductor laser output by chirp due to temporal change in the refractive

index is decreased. The EOM160C emits a pulse light modulated in synchronous with the voltage pulse impressed from the light amount controller 16C. For example, if the EOM160C modulates the laser beam oscillated from the DFB semiconductor laser 160A into a pulse light with a pulse width of 1ns and a repetition frequency of 100kHz (pulse period around 10μs), as a result of this optical modulation, the peak output of the pulse light emitted from the EOM160 is 20mW, and the average output 2μW. In this case, the insertion of the EOM160C does not create any loss, however, in the case there is a loss by insertion, for example, when the loss is -3dB, the peak output of the pulse light becomes 10mW, and the average output 1μW.

[0084]

In the case of setting the repetition frequency to around 100kHz and over, it is preferable to prevent the amplification reduction due to the noise effect of the ASE (Amplified Spontaneous Emission) with the fiber amplifier. The details on this will be described later on in the description.

[0085]

When only the EOM160C is used and the pulse light is turned off, in the case the extinction ratio is not sufficient enough, it is preferable to use the current control of the DFB semiconductor laser 160A. That is, since with semiconductor lasers and the like, the emitted light can be pulse oscillated by performing current

control, it is preferable to generate the pulse light by utilizing both the current control of the DFB semiconductor laser 160A and the EOM160C. For example, if a pulse light having a width of around 10 - 20 ns is oscillated by the current control of the DFB semiconductor laser 160A and is partially extracted and modulated by the EOM160C into a pulse light having a width of around 1ns, it becomes possible to generate a pulse light that has a narrow pulse width compared with the case when using only the EOM160C, and can also further simplify the control of the oscillation interval and the beginning/end of the oscillation of the pulse light.

[0086]

Alternately, it is possible to use an acousto-optic modulator (AOM) instead of the EOM160C.

[0087]

The light amplifying portion 161 amplifies the pulse light from the EOM160C, and in this case, is structured including a plurality of fiber amplifiers. An example of the arrangement of the light-amplifying portion 161 is shown in Fig. 3 with the EOM160C.

[0088]

As shown in Fig. 3, the light amplifying portion 161 comprises: a branch and delay portion 167, which has a total of 128 channels from the channels 0 to 127; fiber amplifiers 168_1 - 168_{128} which are respectively connected to the output side of the channels 0 to 127 (a total of

128 channels) of the branch and delay portion 167; narrow-band filters 169_1 - 169_{128}, optical isolators 170_1 - 170_{128}, fiber amplifiers 171_1 - 171_{128}, which are connected to the output side of the fiber amplifiers 168_1 - 168_{128} in this order, and the like. In this case, as is obvious from Fig. 3, the fiber amplifier 168_n, the narrow-band filter 169_n, the optical isolator 170_n, and the fiber amplifier 171_n (n=1, 2, ..., 128) respectively make up the optical path 172_n (n=1, 2, ..., 128).

[0089]

To further describe each structuring portion of the light amplifying portion 161, the branch and delay portion 167 has a total of 128 channels, and provides a predetermined delay time (in this case 3ns) to the output of each channel. In this embodiment, the structure of the branch and delay portion 167 includes: an erbium (Er)-doped fiber amplifier (EDFA), which performs a 35dB (x 3162) optical amplification on the pulse light emitted from the EOM160C; a splitter (1 planar waveguide x 4 splitters) serving as an optical branch unit which divides in parallel the output of the EDFA into four (channels 0 to 3) outputs; four optical fibers with different lengths, which are respectively connected to the output end of the channels 0 to 3 of the splitter; four splitters (1 planar waveguide x 32 splitters) which divides the output of the four optical fibers respectively into 32 (channels 0 to 31); and 31 optical fibers each (a total of 124 optical fibers) having

different lengths, which are respectively connected to the channels 1 to 31 (excluding channel 0) of each splitter. Hereinafter, the channels 0 to 31 of each splitter (1 planar waveguide x 32 splitters) will be referred to as a "block" in general.

[0090]

More particularly, the pulse light emitted from the EDFA has a peak output of around 63W, and the average output is around 6.3W. This pulse light is divided in parallel into four outputs, to channel 0 to 3 by the splitter (1 planar waveguide x 4 splitters), and a delay corresponding to the length of the four optical fibers is provided to the light emitted from each channel. For example, in the embodiment, when the propagation velocity of light in the optical fiber is 2 x 10^8m/s, and the length of the optical fibers connected to the channels 0, 1, 2, and 3 of the splitter (1 planar waveguide x 4 splitters) are 0.1m, 19.3m, 38.5m, and 57.7m respectively (hereinafter referred to as the "first delay fiber"), then the delay of light between adjacent channels at the emitting side of the first delay fiber is 96ns.

[0091]

In addition, to the channels 1 to 31 of the four splitters (1 splitter: 1 planar waveguide x 32 splitters), optical fibers (hereinafter referred to as the "second delay fiber") respectively having the length of 0.6 x N (N = channel number) are connected. As a consequence, a delay of 3ns is provided between adjacent channels within

each block. And in respect to the output of channel 0 in each block, a delay of 3x31=93ns is provided to the output of channel 31.

[0092]

Meanwhile, in between each block, from the first block to the fourth block, the first delay fiber respectively provides a delay of 96ns at the input stage of each block, as is described above. Accordingly, the channel 0 output of the second block is provided a delay of 96ns in respect to the channel 0 output of the first block, and a delay of 3ns in respect to the channel 31 output of the first block. This is likewise, between the second and third block, and the third and fourth block. And as a consequence, as the entire output, on the emitting side of the 128 channels, a pulse light that has a 3ns delay in between adjacent channels can be obtained.

[0093]

From the branch and delay described above, on the emitting side of the 128 channels, the pulse light that has a 3ns delay in between adjacent channels is obtained, and the light pulse that can be observed at each emitting end is 100kHz (pulse period 10μs), which is the same as the pulse modulated by the EOM 160C. Accordingly, from the viewpoint of the entire laser beam generating portion, the repetition of the next pulse train being generated at an interval of 9.62μs after 128 pulses are generated at an interval of 3ns, is performed at 100kHz. That is, the total output becomes $128 \times 100 \times 10^3 = 1.28 \times 10^7$ pulse/second.

[0094]

With the embodiment, the example was of the case when the channel was divided into 128 and the delay fibers used were short, thus, in between pulse trains an interval of 9.62μs occurred where no light was emitted. However, by increasing the number of divided channels, or by using a longer delay fiber with an appropriate length, or by combining both methods, it is possible to make the pulse interval completely equal.

[0095]

In the embodiment, the erbium (Er)-doped fiber amplifier (EDFA) which mode field diameter of the optical fiber (hereinafter referred to as "mode diameter") is 5 - 6μm, likewise with the optical fiber normally used for communication, is used as the fiber amplifier 168_n (n=1, 2, ..., 128). The fiber amplifier 168_n amplifies the emitted light from each channel of the branch and delay portion 167 according to a predetermined amplifier gain. The pumped light source and the like of the fiber amplifier 168_n will be described later in the description.

[0096]

The narrow-band filter 169_n (n=1, 2, ..., 128) cuts the ASE generated at the fiber amplifier 168_n while allowing the output wavelength (wavelength width around 1pm or under) of the DFB semiconductor laser 160A to pass, so that the wavelength width of the light transmitted is substantially narrowed. This can prevent the amplifier gain being reduced by the ASE being incident on the fiber

amplifier 171_n arranged on the output side, or the laser beam from scattering due to traveling the noise of the ASE. It is preferable for the narrow-band filter 169_n to have a transmission wavelength width of around 1pm, however, since the wavelength width of the ASE is around several tens (nm) the ASE can be cut with the current narrow-band filter having the transmission wavelength width of around 100pm to an extent so that there are substantially no serious problems.

[0097]

In addition, in the embodiment, since there are cases when the output wavelength of the DFB semiconductor laser 160A is positively changed, as will be described later, it is preferable to use a narrow-band filter that has a transmission wavelength width (the same level or above the variable width) in accordance with the variable width of the output wavelength (the variable width of the exposure apparatus in the embodiment is, for example, around ±20pm). With the laser unit applied in the exposure apparatus, the wavelength width is set around 1pm and under.

[0098]

The optical isolator 170_n (n=1, 2, ..., 128) reduces the effect of the returning light, likewise with the optical isolator 160B described earlier.

[0099]

As the fiber amplifier 171_n (n=1, 2, ..., 128), in the embodiment, in order to avoid the spectral width of

the amplified light from increasing due to the nonlinear effect in the optical fiber, the mode diameter of the optical fiber used is wider than the optical fiber normally used for communication (5 - 6μm). For example, an EDFA with a wide diameter of around 20 - 30μm is used. The fiber amplifier 171_n further amplifies the light emitted from each channel of the branch and delay portion 167 that have already been amplified with the fiber amplifier 168_n. As an example, when the average output of each channel of the branch and delay portion 167 is around 50μW and the average output of all the channels is around 6.3mW, and an amplification of a total of 46dB (x 40600) is performed by the fiber amplifier 168_n and the fiber amplifier 171_n, at the output end of the optical path 172_n corresponding to each channel (the output end of the optical fiber making up the fiber amplifier 171_n), the peak output of 20kW, the pulse width 1ns, the pulse repetition frequency 100kHz, the average output 2W, and the average output of all the channels 256W are obtained. The pumped light source and the like of the fiber amplifier 171_n will also be described later in the description.

[0100]

In the embodiment, the output end of the optical path 172_n corresponding to each channel of the branch and delay portion 167, that is, the output end of the optical fiber making up the fiber amplifier 171_n, is bundled to form a bundle-fiber 173, which has a sectional shape as is shown

in Fig. 4. The cladding diameter of each optical fiber is around 125μm, therefore, the diameter of the bundle of 128 optical fibers at the output end can be around 2mm or under. In the embodiment, the bundle-fiber 173 is formed using the output end of the fiber amplifier 171_n itself, however, a non-doped optical fiber can be connected to each output end of the fiber amplifier 171_n and the bundle-fiber can be formed by bundling these optical fibers.

[0101]

The fiber amplifier 168_n that has an average mode diameter and the fiber amplifier 171_n that has a wide mode diameter are connected using an optical fiber which mode diameter increases in the shape of a truncated cone.

[0102]

Next, the pumped light source and the like of each fiber amplifier are described with reference to Fig. 5. Fig. 5 schematically shows the fiber amplifiers and their neighboring area structuring the light amplifying portion 161, with a partial view of the wavelength conversion portion 163.

[0103]

In Fig. 5, a semiconductor laser 178 for pumping is fiber coupled to the fiber amplifier 168_n, and the output of the semiconductor laser 178 is input into the doped fiber for the fiber amplifier through the wavelength division multiplexer (WDM) 179. The doped fiber is pumped with this operation.

[0104]

Meanwhile, with the fiber amplifier 171_n having a wide mode diameter, a semiconductor laser 174 that serves as a pumping light source to pump the doped fiber for the fiber amplifier having a wide mode diameter is fiber coupled to the fiber with the wide mode diameter, which diameter matches that of the doped fiber for the fiber amplifier. And the output of the semiconductor laser 174 is input to the doped fiber for the optical amplifier, and thus the doped fiber is pumped.

[0105]

The laser beam amplified with the wide mode diameter (fiber amplifier) 171_n is incident on the wavelength conversion portion 163, and the wavelength of the laser beam is converted to generate the ultraviolet laser beam. The arrangement of the wavelength conversion portion and the like will be described, later in the description.

[0106]

It is preferable for the laser beam (signals) transmitted through the wide mode diameter (fiber amplifier) 171_n to be mainly in the fundamental mode, and this can be achieved by selectively pumping the fundamental mode in a single mode or multimode fiber with a low mode order.

[0107]

With the embodiment, four high-powered semiconductor lasers are fiber coupled to the wide mode diameter fiber in both the proceeding direction of the laser beam

(signals) and the direction opposite. In this case, in order to effectively couple the semiconductor laser beam for pumping to the doped fiber for optical amplification, it is preferable to use an optical fiber which cladding has a double structure as the doped fiber for optical amplification. And, the semiconductor laser beam for pumping is guided into the inner cladding of the dual cladding by the WDM 176.

[0108]

The semiconductor lasers 178 and 174 are controlled by the light amount controller 16C.

[0109]

In addition, in the embodiment, since the fiber amplifiers 168_n and 171_n are provided as the optical fiber making up the optical path 172_n, the gain difference in each fiber amplifier becomes the dispersion of the light emitted at each channel. Therefore, in the embodiment, the output is partially branched at the fiber amplifier of each channel (168_n and 171_n) and is photo-electrically converted by the photoconversion elements 180 and 181 arranged respectively at the branched end. And the output signals of these photoconversion elements 180 and 181 are sent to the light amount controller 16C.

[0110]

The light amount controller 16C feedback controls the drive current of each pumping semiconductor laser (178 and 174) so that the light emitted from each fiber amplifier is constant (that is, balanced) at each

amplifying stage.

[0111]

Furthermore, with the embodiment, as is shown in Fig. 5, the laser beam split by the beam splitter halfway through the wavelength conversion portion 163 is photo-electrically converted by the photoconversion element 182, and the output signal of the photoconversion element 182 is sent to the light amount controller 16C. The light amount controller 16C then monitors the light intensity of the wavelength conversion portion 163 based on the output signals of the photoconversion element 182, and feedback controls the drive current of at least either the pumping semiconductor laser 178 or the pumping semiconductor laser 174 so that the light output from the wavelength conversion portion 163 becomes a predetermined light output.

[0112]

By having this arrangement, since the amplification of the fiber amplifier in each channel is constant at each amplifying stage, a unified light intensity can be obtained as a whole without an overload on either fiber amplifier. In addition, by monitoring the light intensity of the wavelength conversion portion 163, the expected predetermined light intensity can be fed back to each amplifier, and the desired ultraviolet light output can be stably obtained.

[0113]

Details on the light amount controller 16C will be

described later in the description.

[0114]

From the light amplifying portion 161 (the output side of each optical fiber forming the bundle-fiber 173) having the arrangement described above, the pulse light is emitted, on which circular polarization has been performed. The circular polarized pulse light is converted to a linear polarized pulse light where the polarized direction is all the same by the quarter-wave plate 162 (refer to Fig. 2), and is then incident on the wavelength conversion portion 163.

[0115]

The wavelength conversion portion 163 includes a plurality of nonlinear optical crystals, and converts the wavelength of the amplified pulse light (light having the wavelength of 1.544μm) into an eighth-harmonic wave or a tenth-harmonic wave so that ultraviolet light that has the same output wavelength as the ArF excimer laser (wavelength: 193nm) or the F_2 laser (wavelength: 157nm) is generated.

[0116]

Fig. 6(A) and Fig. 6(B) show examples of the arrangement of the wavelength conversion portion 163. Following is a description of concrete examples on the wavelength conversion portion 163, with reference to these Figures.

[0117]

Fig. 6(A) shows an example of the arrangement when

ultraviolet light having the same wavelength as the ArF excimer laser (193nm) is generated by converting the fundamental wave of the wavelength 1.544μm output from the emitting end of the bundle-fiber 173 using the nonlinear optical crystals into an eighth-harmonic wave. In addition, Fig. 6(B) shows an example of the arrangement when ultraviolet light having the same wavelength as the F_2 laser (157nm) is generated by converting the fundamental wave of the wavelength 1.57μm output from the emitting end of the bundle-fiber 173 using the nonlinear optical crystals into a tenth-harmonic wave.

[0118]

At the wavelength conversion portion in Fig. 6(A), the wavelength conversion is performed in the order of: fundamental wave (wavelength: 1.544μm) → second-harmonic wave (wavelength: 772nm) → third-harmonic wave (wavelength: 515nm) → fourth-harmonic wave (wavelength: 386nm) → seventh-harmonic wave (wavelength: 221nm) → eighth-harmonic wave (wavelength: 193nm).

[0119]

More particularly, the fundamental wave output from the emitting end of the bundle-fiber 173 that has the wavelength of 1.544μm (frequency ω) is incident on the first stage nonlinear optical crystal 533. When the fundamental wave passes through the nonlinear optical crystal 533, by the second-harmonic generation a second-harmonic wave which frequency is doubled from the

frequency ω of the fundamental wave, that is, a second-harmonic wave with a frequency of 2ω (the wavelength is half, which is 772nm) is generated.

[0120]

As the first stage nonlinear optical crystal 533, an LiB_3O_5(LBO) crystal is used, and NCPM (Non-Critical Phase Matching), which is a method of adjusting the temperature of the LBO crystal for phase matching to convert the wavelength of the fundamental wave to a second-harmonic wave, is employed. NCPM is capable of converting the fundamental wave into a second-harmonic wave with high efficiency, since walk-off between the fundamental wave and the second-harmonic wave does not occur within the nonlinear optical crystal, and also because of the advantage that the beam shape of the second-harmonic wave generated does not change by the walk-off.

[0121]

The fundamental wave that has passed through the nonlinear optical crystal 533 without the wavelength converted and the second-harmonic wave generated by the wavelength conversion are respectively provided a delay of a half wave and a single wave at a wavelength plate 534 at the next stage.. Only the fundamental wave rotates the polarized direction by 90 degrees, then the fundamental wave and the second-harmonic wave are incident on the second stage nonlinear optical crystal 536. As the second nonlinear optical crystal 536, an LBO crystal is used, and the LBO crystal is used in NCPM at a

temperature different from the first nonlinear optical crystal (LBO crystal) 533. In the nonlinear optical crystal 536, a third-harmonic wave (wavelength: 515nm) is generated by sum frequency generation of the second-harmonic wave generated in the first nonlinear optical crystal 533 and of the fundamental wave that has passed through the nonlinear optical crystal 533 without the wavelength converted.

[0122]

Then, the third-harmonic wave obtained in the nonlinear optical crystal 536 and the fundamental wave and the second-harmonic wave that have passed through the nonlinear optical crystal 536 without being converted are separated at the dichroic mirror 537, and the third-harmonic wave reflected on the dichroic mirror 537 passes through the condenser lens 540 and the dichroic mirror 543 and is incident on the fourth stage nonlinear optical crystal 545. Meanwhile, the fundamental wave and the second-harmonic wave that have passed through the dichroic mirror 537 passes through a condenser lens 538 and are incident on the third stage nonlinear optical crystal 539.

[0123]

The LBO crystal is used as the third stage nonlinear optical crystal 539, and the fundamental wave passes through the LBO crystal without being converted, whereas, the second-harmonic wave is converted to a fourth-harmonic wave (wavelength: 386nm) by second-harmonic

generation. The fourth-harmonic wave obtained in the third nonlinear optical crystal 539 and the fundamental wave that has passed through the third nonlinear optical crystal 539 are separated at the dichroic mirror 541, and the fundamental wave that has passed through the dichroic mirror 541 passes through the condenser lens 544 and is reflected on the dichroic mirror 546, and is incident on the fifth stage nonlinear optical crystal 548. On the other hand, the fourth-harmonic wave reflected on the dichroic mirror 541 passes through the condenser lens 542 and reaches the dichroic mirror 543, and is coaxially synthesized with the third-harmonic wave reflected on the dichroic mirror 537 and then is incident on the fourth stage nonlinear optical crystal 545.

[0124]

As the fourth stage nonlinear optical crystal 545, a β-BaB_2O_4(BBO) crystal is used, and a seventh-harmonic wave (wavelength: 221nm) is generated by sum frequency generation of the third-harmonic wave and the fourth-harmonic wave. The seventh-harmonic wave generated in the fourth nonlinear optical crystal 545 passes through the condenser lens 547, and is coaxially synthesized with fundamental wave that has passed through the dichroic mirror 541 at the dichroic mirror 546, and is then incident on the fifth stage nonlinear optical crystal 548.

[0125]

As the fifth stage nonlinear optical crystal 548, the LBO crystal is used, and an eighth-harmonic wave

(wavelength: 193nm) is generated by sum frequency generation of the fundamental wave and the seventh-harmonic wave. In the arrangement above, instead of the BBO crystal 545 used to generate the seventh-harmonic wave and the LBO crystal 548 used to generate the eight-harmonic wave, it is also possible to use a $CsLiB_6O_{10}$ (CLBO) crystal and a $Li_2B_4O_7$ (LB4) crystal.

[0126]

With the arrangement example in Fig. 6(A), since the third-harmonic wave and the fourth-harmonic wave proceed through different optical paths and are incident on the fourth stage nonlinear optical crystal 545, the lens 540 to condense the third-harmonic wave and the lens 542 to condense the fourth-harmonic wave can be arranged on separate optical paths. The sectional shape of the fourth-harmonic wave generated in the third nonlinear optical crystal 539 is elliptic due to the walk-off phenomenon. Therefore, in order to obtain favorable conversion efficiency in the fourth stage nonlinear optical crystal 545, it is preferable to perform beam shaping on the fourth-harmonic wave. In this case, since the condenser lens 540 and 542 are arranged on different optical paths, for example, a pair of cylindrical lens can be used as the lens 542 to easily perform beam shaping on the fourth-harmonic wave. This makes it possible for the fourth-harmonic wave to overlap the third-harmonic wave favorably at the fourth stage nonlinear optical crystal 545, and the conversion

efficiency can be increased.

[0127]

Furthermore, the lens 544 to condense the fundamental wave incident on the fifth stage nonlinear optical crystal 548 and the lens 547 to condense the seventh-harmonic wave can be arranged on different optical paths. The sectional shape of seventh-harmonic wave generated in the fourth stage nonlinear optical crystal 545 is elliptic due to the walk-off phenomenon. Therefore, in order to obtain favorable conversion efficiency in the fifth stage nonlinear optical crystal 548, it is preferable to perform beam shaping on the seventh-harmonic wave. In the embodiment, since the condenser lens 544 and 547 can be arranged on different optical paths, for example, a pair of cylindrical lens can be used as the lens 547 to easily perform beam shaping on the seventh-harmonic wave. Thus, the seventh-harmonic wave can favorably overlap the fundamental wave at the fifth stage nonlinear optical crystal (LBO crystal) 548, and the conversion efficiency can be increased.

[0128]

The structure in between the second stage nonlinear optical crystal 536 and the fourth stage nonlinear optical crystal 545 is not limited to the arrangement shown in Fig. 6(A). It can have any arrangement, so long as the third-harmonic wave, generated in the nonlinear optical crystal 536 and reflected on the dichroic mirror 537, and the fourth-harmonic wave, obtained by converting

the wavelength of the second-harmonic wave generated in the nonlinear optical crystal 536 which passes through the dichroic mirror 537 in the nonlinear optical crystal 539, are both incident at the same time on the nonlinear optical crystal 545, and the length of the optical paths in between both nonlinear optical crystals 536 and 545 is equal. The same can be said of the structure in between the third stage nonlinear optical crystal 539 and the fifth stage nonlinear optical crystal 548.

[0129]

According to an experiment performed by the inventor, in the case of Fig. 6(A), the average output of the eighth-harmonic wave (wavelength: 193nm) in each channel was around 45.9mW. Accordingly, the average output of the bundle of the entire 128 channels becomes 5.9W, therefore, ultraviolet light having a wavelength of 193nm can be provided, which is sufficient enough as an output of a light source for an exposure apparatus.

[0130]

In this case, on generating an eighth-harmonic wave (wavelength: 193nm), currently, the LBO crystal, which has good quality and can be purchased easily on the market, is used. Since the LBO crystal has an extremely small absorption coefficient to the ultraviolet light having a wavelength of 193nm, and the optical damage of the crystal does not create a serious problem, the LBO crystal is advantageous in durability.

[0131]

In addition, at the generating portion of the eighth-harmonic wave (wavelength: 193nm), angular phase matching is performed on the LBO crystal used, however, since the phase matching angle is large, the effective nonlinear optical constant (d_{eff}) becomes small. Therefore, it is preferable to use the LBO crystal at a high temperature by providing a temperature control mechanism to the LBO crystal. This can reduce the phase matching angle, that is, the constant referred to above (d_{eff}) can be increased, and the generation efficiency of the eighth-harmonic wave can be improved.

[0132]

At the wavelength conversion portion in Fig. 6(B), the wavelength conversion is performed in the order of: fundamental wave (wavelength: 1.57μm) → second-harmonic wave (wavelength: 785nm) → fourth-harmonic wave (wavelength: 392.5nm) → eighth-harmonic wave (wavelength: 196.25nm) → tenth-harmonic wave (wavelength: 157nm). In this arrangement example, upon each wavelength conversion from the second-harmonic wave generation to the eighth-harmonic wave generation, second-harmonic generation is performed on each wavelength when it enters each wavelength conversion.

[0133]

Also, in this arrangement example, as the nonlinear optical crystal used for wavelength conversion, the LBO crystal is used for the nonlinear optical crystal 602 that generates a second-harmonic wave from a fundamental

wave by second-harmonic generation, and for the nonlinear optical crystal 604 that generates a fourth-harmonic wave from the second-harmonic wave by second-harmonic generation. Furthermore, as the nonlinear optical crystal 609, which generates an eighth-harmonic wave from the fourth-harmonic wave by second-harmonic generation, an $Sr_2Be_2B_2O_7$(SBBO) crystal is used. And, as the nonlinear optical crystal 611, which generates a tenth-harmonic wave (wavelength: 157nm) by sum frequency generation of the second-harmonic wave and the eighth-harmonic wave, the SBBO crystal is used.

[0134]

The second-harmonic wave generated in the nonlinear optical crystal 602 passes through the condenser lens 603 and is incident on the nonlinear optical crystal 604, and the nonlinear optical crystal 604 generates the fourth-harmonic wave described above, as well as a second-harmonic wave that is not converted. The second-harmonic wave, which has passed through the dichroic mirror 605, then passes through the condenser lens 606 and is reflected on the dichroic mirror 607, and then is incident on the nonlinear optical crystal 611. Whereas, the fourth-harmonic wave, which is reflected on the dichroic mirror 605, passes through the condenser lens 608 and is incident on the nonlinear optical crystal 609, and the eighth-harmonic wave generated in the nonlinear optical crystal 609 proceeds to the condenser lens 610 and the dichroic mirror 607, and then is incident on the

nonlinear optical crystal 611. Furthermore, the nonlinear optical crystal 611 generates the tenth-harmonic wave (wavelength: 157nm) by sum frequency generation of the second-harmonic wave and the eighth-harmonic wave, which are coaxially synthesized at the dichroic mirror 607.

[0135]

In this arrangement example, the arrangement was made so that the second-harmonic wave and the fourth-harmonic wave generated in the second stage nonlinear optical crystal 604 were separated at the dichroic mirror 605, and the second-harmonic wave having passed through the dichroic mirror 605 and the eighth-harmonic wave obtained by converting the wavelength of the fourth-harmonic wave at the nonlinear optical crystal 609 went through different optical paths before being incident on the fourth stage nonlinear optical crystal 611. Alternately, the dichroic mirrors 605 and 607 do not have to be used, and the four nonlinear optical crystals 602, 604, 609, and 611 may have a coaxial arrangement.

[0136]

However, in the arrangement example, the sectional shape of the fourth-harmonic wave generated in the second stage nonlinear optical crystal 604 is elliptic due to the walk-off phenomenon. Therefore, in order to obtain favorable conversion efficiency in the fourth stage nonlinear optical crystal 611 where this beam is incident, it is preferable to perform beam shaping on the fourth-harmonic wave, which is the incident beam, and create a

favorable overlap with the second-harmonic wave. In this arrangement example, since the condenser lenses 606 and 608 are arranged on different optical paths, for example, it is possible to use the cylindrical lens as the lens 608, which makes the beam shaping of the fourth-harmonic wave easier. Thus, the fourth-harmonic wave can favorably overlap the second-harmonic wave at the fourth stage nonlinear optical crystal 611, and the conversion efficiency can be increased.

[0137]

It is a matter of course, that the wavelength conversion portion shown in Figs. 6(A) and 6(B) are mere examples, and the arrangement of the wavelength conversion portion in the present invention is not limited to them.

[0138]

Referring back to Fig. 2, the beam monitor mechanism 164 is made up of a Fabry-Perot etalon (hereinafter also referred to as "etalon element") and an energy monitor consisting of a photoconversion element such as a photodiode (neither is shown in Figs.). The beam incident on the etalon element structuring the beam monitor mechanism 164 passes through the etalon element with a transmittance that corresponds to the frequency difference of the resonance frequency of the etalon element and the frequency of the incident beam. And the output signals of the photodiode and the like, which detect the intensity of the transmitted beam, are sent to

the laser controller 16B. The laser controller 16B performs a predetermined signal processing on the output signals, and obtains information related to the optical properties of the incident beam on the beam monitor mechanisms 164, to be precise, on the etalon element (to be concrete, information such as the center wavelength of the incident beam and the width of the wavelength (spectral half-width)). And the information related to the optical properties is sent to the main controller 50 realtime.

[0139]

The frequency characteristic of the transmitted light intensity that the etalon element generates is affected by the temperature or pressure of atmosphere, and in particular, the resonance frequency (resonance wavelength) is temperature dependent. Therefore, it is important to study the temperature dependence of the resonance wavelength in order to precisely control the center wavelength of the laser beam oscillated from the laser light source 160A based on the detection results of the etalon element. In the embodiment, the temperature dependence of the resonance wavelength is measured in advance, and the measurement results are stored as a temperature dependence map in the memory 51 (refer to Fig. 1) serving as a storage unit, which is arranged with the main controller 50. The temperature dependence map can have the form of a table, or be a function or a coefficient in the memory 51.

[0140]

And, the main controller 50 gives instructions to the laser controller 16B to positively control the temperature of the etalon element within the beam monitor mechanism 164, so that the resonance wavelength (detection reference wavelength) maximizing the transmittance of the etalon element precisely coincides with the wavelength set in cases such as absolute wavelength calibration of the beam monitor mechanism 164, which will be described later on.

[0141]

In addition, the output of the energy monitor structuring the beam monitor mechanism 164 is sent to the main controller 50, and the main controller 50 detects the energy power of the laser beam based on the output of the energy monitor and controls the light amount of the laser beam oscillated from the DFB semiconductor laser 160A via the laser controller 16B or turns off the DFB semiconductor laser 160A when necessary. In the embodiment, however, as will be described later on, the light amount control (exposure amount control) is usually performed mainly by the light amount controller 16C, by controlling the peak power or frequency of the pulse light emitted from the EOM160C or by on/off control of the light emitted from each fiber amplifier structuring the light amplifying portion 161. Accordingly, the main controller 50 controls the laser controller 16B in the manner described above when the energy power of the laser

beam changes greatly for some reason.

[0142]

The absorption cell 165 is an absolute wavelength source for absolute wavelength calibration of the oscillation wavelength of the DFB semiconductor laser 160A, in other words, is the absolute wavelength source for absolute wavelength calibration of the beam monitor mechanism 164. In the embodiment, since the DFB semiconductor laser 160A having the oscillation wavelength of 1.544μm is used as the laser light source, an isotope of acetylene having dense absorption lines in the wavelength band around the wavelength of the DFB semiconductor laser 160A is used as the absorption cell 165.

[0143]

As will be described later on, in the case of selecting intermediate waves of the wavelength conversion portion 163 (such as the second-harmonic wave, the third harmonic wave, and the fourth harmonic wave) or light which wavelength has been converted with, or in alternate of the fundamental wave as the light for monitoring the wavelength of the laser beam, the absorption cell that has dense absorption lines around the wavelength of the intermediate wave can be used. For example, in the case of selecting the third-harmonic wave as the light for monitoring the wavelength of the laser beam, iodine molecules that have dense absorption lines around the wavelength of 503nm to 530nm can be used as the

absorption cell. The appropriate absorption line of the iodine molecules can be chosen, and the wavelength of the absorption line can be determined as the absolute wavelength.

[0144]

In addition, the absolute wavelength source is not limited to the absorption cell, and the absolute wavelength light source may also be used.

[0145]

The laser controller 16B detects the center wavelength and the spectral half-width of the laser beam based on the output of the beam monitor mechanism 164 under the control of the main controller 50, and feedback controls the temperature control and current control of the DFB semiconductor laser 160A so that the center wavelength becomes a desired value (set wavelength). In the embodiment, it is possible to control the temperature of the DFB semiconductor laser 160A in the unit of 0.001°C.

[0146]

In addition, the laser controller 16B switches the output of the DFB semiconductor 160A between the pulse output and the continuous output and controls the output interval and pulse width during pulse output, as well as control the oscillation of the DFB semiconductor laser 160A so as to compensate the output variation of the pulse light, in accordance with instructions from the main controller 50.

[0147]

In this manner, the laser controller 16B stabilizes the oscillation wavelength to a constant wavelength, as well as finely adjust the output wavelength. On the contrary, the laser controller 16B may also adjust the output wavelength of the DFB semiconductor laser 160A by positively changing the oscillation wavelength in accordance with instructions from the main controller 50. The details on this will be described further later on.

[0148]

Next, the wavelength stabilizing control method of the laser beam oscillated by the DFB semiconductor laser will be described.

[0149]

First of all, the absolute wavelength calibration of the etalon element in the beam monitor mechanism 164, which is the premise of the wavelength stabilizing control, will be described.

[0150]

As was described earlier, in the embodiment, the oscillation wavelength of the DFB semiconductor laser 160A and the temperature dependence of the resonance wavelength (λ_{res}) of the etalon element in the beam monitor mechanism 164 is measured in advance, and the measurement results are stored in the memory 51.

[0151]

On absolute wavelength calibration of the etalon element, the main controller 50 selects the absorption line that has the wavelength closest to the set

wavelength (λ_{set}) maximizing the transmittance of the absorption cell 165 via the laser controller 16B or the absorption line that has the wavelength coinciding with the set wavelength (λ_{ref}) in a state where the DFB semiconductor laser 160A is oscillated via the laser controller 16B. And during this operation, the main controller 50 gives instructions to the laser controller 16B to control the temperature of the etalon element in the beam monitor mechanism 164, so that the transmittance of the etalon element is at the maximum. That is, the calibration is performed with the resonance wavelength (λ_{res}) of the etalon element utilizing the absolute wavelength (λ_{ref}). Thus, λ_{res}, which is the detection reference wavelength of the etalon element, coincides with the absolute wavelength (λ_{ref}).

[0152]

When the absolute wavelength calibration is performed, the main controller may change the oscillation wavelength of the DFB semiconductor laser 160A within a predetermined range via the laser controller 16B. With this arrangement, even if the oscillation wavelength of the DFB semiconductor laser 160A is greatly off the set wavelength at the time of starting the oscillation, it becomes possible to swiftly select the absorption line that has the wavelength closest to the set wavelength (λ_{set}) maximizing the transmittance of the absorption cell 165 or the absorption line that has the wavelength coinciding with the set wavelength (λ_{ref}). As a

consequence, the absolute wavelength calibration can be completed within a short period of time.

[0153]

And, when the absolute wavelength calibration is completed, the main controller 50 controls the temperature of the etalon element via the laser controller 16B, using the data on temperature dependence of the resonance wavelength (λ_{res}) of the etalon element stored in the memory 51, and performs set wavelength calibration to set the resonance wavelength (λ_{res}) of the etalon element at the set wavelength (λ_{set}).

[0154]

With the wavelength stabilizing control method in the embodiment, the resonance wavelength (λ_{res}) of the etalon element, in other words, the detection reference wavelength can coincide with the set wavelength without fail.

[0155]

And, after this is completed, the laser controller 16B controls the temperature and current of the DFB semiconductor laser 160A by feedback control based on the detection values of the etalon element (monitoring results of the beam monitor mechanism 164) having completed the set wavelength calibration. The reason why the laser controller 16B controls the current supplied (drive current) of the DFB semiconductor laser 160A, as well as the temperature, is because the responsiveness is better in current control.

[0156]

The light amount controller 16C has the following functions: stabilizing the amplification of the fiber amplifiers at each channel at each amplifying stage, by performing feedback control on the drive current of each pumping semiconductor laser (178 and 174) based on the output of the photoconversion elements 180 and 181 that detect the light emitted from the fiber amplifiers 168_n and 171_n within the light amplifying portion 161; and stabilizing the desired ultraviolet output by performing feedback control on the drive current of at least either the pumping semiconductor laser 178 or the pumping semiconductor laser 174 and feeding back the predetermined light intensity expected to each amplifying stage, based on the output signal of the photoconversion element 182, which detects the light split by the beam splitter along the wavelength conversion portion 163.

[0157]

Furthermore, in the embodiment, the light amount controller 16C has the following functions.

[0158]

That is, the light amount controller 16C has the functions of:

① Controlling the average light output of the bundle in total by performing individual on/off control on the output of the fiber of each channel making up the bundle-fiber 173, in other words, the output of each optical path 172_n, in accordance with instructions from the main

controller 50 (hereinafter referred to as the "first function" for the sake of convenience);

② Controlling the average light output (output energy) per unit time of each channel in the light amplifying portion 161, in other words, the intensity of the light emitted per unit time from each optical path 172_n, by controlling the frequency of the pulse light emitted from the EOM160C in accordance with instructions from the main controller 50 (hereinafter referred to as the "second function" for the sake of convenience); and

③ Controlling the average light output (output energy) per unit time of each channel in the light amplifying portion 161, in other words, the intensity of the light emitted per unit time from each optical path 172_n, by controlling the peak power of the pulse light emitted from the EOM160C in accordance with instructions from the main controller 50 (hereinafter referred to as the "third function" for the sake of convenience).

[0159]

Details of the first, second, and third functions will now be described.

[0160]

First of all, the light amount controller 16C performs the on/off operation on each optical path 172_n referred to in the first function, by performing the on/off operation on the output of each channel of the fiber amplifier 171_n. In this case, the light amount controller 16C can perform the operation by performing

on/off operation on the fiber amplifier pumping semiconductor laser 174, in other words, by selectively setting the intensity of the pumped light from the semiconductor laser 174 to either a predetermined level or to a zero level. Or, the light amount controller 16C can perform the operation by adjusting the drive current value of the semiconductor laser 174 so that the intensity of the pumped light from the semiconductor laser 174 is selectively set to a first level where the fiber amplifier 171_n is in a state capable of amplifying, or to a second level where the fiber amplifier 171_n is not in a state capable of amplifying. In the state not capable of amplifying, the light absorption becomes larger, and the output from the fiber amplifier is almost zero, therefore, the output of each optical path 172_n is turned off.

[0161]

In the case of performing on/off operation on the semiconductor laser 174, when the semiconductor laser 174 is in an off state, no power is consumed, therefore, energy saving becomes possible. On the other hand, in the case of switching the intensity of the pumped light from the semiconductor laser 174 between the first level and the second level, the first level and the second level may be a fixed value, but does not necessarily have to be a fixed value. That is, with the fiber amplifier, the state where it is or is not capable of amplifying is determined by whether the intensity of the pumped light

is above or below a certain value.

[0162]

According to the first function of the light amount controller 16C, the average light output (light amount) of the whole bundle is controllable by $1/128^{th}$ of the maximum light output (by around 1% and under). That is, the dynamic range can be set at a wide range of 1 - 1/128. Since each optical path 172_n is made up of the same structuring material, designwise, the light output of the optical path 172_n is supposed to be equal, therefore light amount control by $1/128^{th}$ is to have good linearity.

[0163]

In addition, with the embodiment, the wavelength conversion portion 163 is arranged to perform wavelength conversion on the output of the light amplifying portion 161, that is, on the output of the bundle-fiber 173. The output of the wavelength conversion portion 163 is proportional to the output of each optical path 172_n, that is, to the number of fibers of the fiber amplifier 171_n in an on state. Therefore, in principle, a linear light amount control by $1/128^{th}$ of the maximum light output (by around 1%) is possible.

[0164]

However, in actual, possibilities are high that the output of each optical path 172_n is dispersed or the wavelength conversion efficiency in respect to the output of each optical path 172_n is dispersed due to manufactural errors and the like. Therefore, the output dispersion of

each optical fiber (optical path 172_n), the output dispersion due to the wavelength conversion efficiency dispersion in respect to the output of each optical fiber and the like are measured in advance. And based on the measurement results, a first output intensity map, which is a map on intensity of light output from the wavelength conversion portion 163 corresponding to the on/off state of the light output of each optical fiber (a conversion table of output intensity corresponding to the fiber group in the "on" state), is made, and stored in the memory 51 arranged along with the main controller 50. The first output intensity map stored in the memory 51, may be in the form of a table, or it may be in the form of a function or a coefficient. It is likewise, with the second and third intensity map, which will be described later in the description.

[0165]

And, the light amount controller performs light amount control based on the set light amount provided from the main controller 50 and the intensity map described above, when performing the light amount control related to the first function.

[0166]

In addition, the light amount controller 16C controls the frequency of the pulse light emitted from the EOM160C in the second function described above by changing the frequency of the rectangular wave (voltage pulse) impressed on the EOM160C. Since the frequency of the

pulse light emitted from the EOM160C coincides with the frequency of the voltage pulse impressed on the EOM160C, the frequency of the pulse light emitted is to be controlled by controlling the impressed voltage.

[0167]

In the embodiment, as is previously described the frequency of the rectangular wave impressed on the EOM160C is 100kHz. For example, if the frequency is increased to 110kHz, then the number of the light pulse per unit time increases by 10%, and the branch and delay portion 167 sequentially divides each pulse to the total of 128 channels, from channel 0 to 127, in the same manner as is described earlier. As a consequence, the pulse light per unit time in each channel increases by 10%, and if the light energy per light pulse is the same, that is, the peak power of the pulse light is constant, then, the output light intensity (light amount) of each optical path 172_n per unit time also increases by 10%.

[0168]

In addition, in the embodiment, the wavelength conversion portion 163, which converts the wavelength of the emitted light from each channel of the light amplifying portion 161, is arranged, and the light amount of the light emitted per unit time of the wavelength conversion portion 163 is proportional to the frequency of the output pulse of each channel, if the peak power is constant. Accordingly, the light amount control of the second function is control with excellent linearity.

[0169]

The pulse light emitted from the EOM160C, however, is input to the fiber amplifiers 168_n and 171_n via the branch and delay portion 167, therefore, in actual, the linearity may not always be as stated above. That is, in general, the amplifier gain of the fiber amplifier has input light intensity dependence, so if the frequency of the output light of the EOM160C is changed, there may be cases where the input light intensity of the fiber amplifiers 168_n and 171_n changes, and as a result, the peak power of the pulse light emitted from the fiber amplifiers 168_n and 171_n may also change. It is possible to suppress the change in peak power by designing the fiber amplifiers 168_n and 171_n appropriately, however, this may reduce the light output efficiency and other performances of the fiber amplifiers.

[0170]

Thus, in the embodiment, the input frequency intensity dependence of the output of fiber amplifiers is measured in advance. And based on this measurement, the second output intensity map, which is a map on intensity of light output from (each channel of) the light amplifying portion 161 corresponding to the frequency of the pulse light input to the light amplifying portion 161 (a conversion table of output intensity of the light amplifying portion 161, corresponding to the frequency of light emitted from the EOM) is made, and stored into the memory 51.

[0171]

And, when the light amount controller 16C performs the light amount control in the second function, the light amount control is performed based on the set light amount provided from the main controller 50 and the second output intensity map described above.

[0172]

In addition, the light amount controller 16C controls the peak power of the pulse light emitted from the EOM160 in the third function described above, by controlling the peak intensity of the voltage pulse impressed on the EOM160C. This is because the peak power of the emitted light from the EOM160C is dependent on the peak intensity of the voltage pulse impressed on the EOM160C.

[0173]

Also, in the embodiment, the wavelength conversion portion 163, which converts the wavelength of the emitted light from each channel of the light amplifying portion 161, is arranged, and the output light intensity of the wavelength conversion portion 163 shows a dependence in a nonlinear shape proportional to the power number of the harmonic order at the maximum, in respect to the peak intensity of the pulse light emitted from each optical fiber (optical path 172_n). For example, on generating light of 193nm by eighth-harmonic generation as is in Fig. 6(A), the output intensity of the light having the wavelength of 193nm shows the intensity change, which is proportional to the peak power of the fiber amplifier

output to the eighth power, at the maximum.

[0174]

In the case of the embodiment, since the dependence of the peak power of the pulse light emitted from the EOM160C in respect to the peak intensity of the voltage pulse impressed on the EOM160C is cos(V), as a consequence, the nonlinear dependence of the wavelength conversion portion 163 described above is eased. Accordingly, with the light source unit having a wavelength conversion portion as in the embodiment, it is meaningful to perform intensity (light amount) control of the light emitted by controlling the peak intensity of the voltage pulse impressed on the EOM160C.

[0175]

However, as is described earlier, the amplifier gain of the fiber amplifier has input light intensity dependence, therefore, if the peak intensity of the pulse light emitted from the EOM160C is changed, there may be cases where the input light intensity of the fiber amplifiers 168_n and 171_n changes, and as a result, the peak power of the pulse light emitted from the fiber amplifiers 168_n and 171_n may also change. It is possible, to suppress the change in peak power by designing the fiber amplifiers 168_n and 171_n appropriately, however, this may reduce the light output efficiency and other performances of the fiber amplifiers.

[0176]

So, in the embodiment, the input pulse peak intensity

dependence of the output of fiber amplifiers is measured in advance. And based on this measurement, the third output intensity map, which is a map on intensity of light output from (each channel of) the light amplifying portion 161 corresponding to the peak intensity of the pulse light input to the light amplifying portion 161 (a conversion table of output pulse light intensity of the light amplifying portion 161, corresponding to the peak intensity of light emitted from the EOM) is made, and stored into the memory 51. The third output intensity map may be an ultraviolet intensity map, which serves as the wavelength conversion portion output.

[0177]

And, when the light amount controller 16C performs the light amount control in the third function, the light amount control is performed based on the set light amount provided from the main controller 50 and the third output intensity map described above.

[0178]

It is possible to arrange another EOM for transmittance control other than the EOM160C at the output side of the DFB semiconductor laser 160A. And the transmittance of the EOM can be changed by changing the voltage impressed to the EOM, so as to change the energy emitted from the light amplifying portion and wavelength conversion portion per unit time.

[0179]

As can be seen from the description so far, in the

second and third function of the light amount controller 16C, finer light amount control of the emitted light from the light source unit 16 is possible when compared with the first function. On the other hand, in the first function, the dynamic range can be set at a wider level, when compared with the second and third function.

[0180]

Therefore, in the embodiment, on the exposure that will be described later on, rough adjustment of the exposure amount is to be performed according to the first function of the light amount controller 16C, and fine adjustment is to be performed using the second and third function. This will be referred to later in the description.

[0181]

Other than the controls above, the light amount controller 16C also controls the start/stop of the pulse output in accordance with instructions from the main controller 50.

[0182]

Referring back to Fig. 1, the illumination optical system 12 comprises: a beam shaping optical system 18; a fly-eye lens system 22 serving as an optical integrator (a homogenizer); an illumination system aperture stop plate 24; a beam splitter 26; a first relay lens 28A; a second relay lens 28B; a fixed reticle blind 30A; a movable reticle blind 30B; a mirror M for deflecting the optical path; a condenser lens 32; and the like.

[0183]

The beam shaping optical system 18 shapes the sectional shape of the light in the ultraviolet region (hereinafter referred to as "laser beam") LB generated by converting the wavelength of light emitted from the light source unit 16 at the wavelength conversion portion 163 so that it is efficiently incident on the fly-eye lens system 22, which is arranged downstream of the optical path of the laser beam LB. The beam shaping optical system 18, for example, is made up of a cylindrical lens or a beam expander (neither is shown in Figs.).

[0184]

The fly-eye lens system 22 is arranged on the optical path of the laser beam LB emitted from the beam shaping optical system 18, and forms a planar light source, that is, a secondary light source, which consists of many light source images (point light sources), to illuminate the reticle R with a uniform illuminance distribution. The laser beam emitted from the secondary light source, is also referred to as "exposure light IL", in this description.

[0185]

In the vicinity of the emitting surface of the fly-eye lens 22, the illumination system aperture stop plate 24, which is made of a plate-shaped member, is arranged. On the illumination system aperture stop plate 24, a plurality of aperture stops are arranged at substantially equal angular intervals. The aperture stops may have an

ordinary circular aperture, or it may have a small circular-shaped aperture for reducing the σ-value, which is a coherence factor. It may also have a ring-shaped aperture for ring-shaped illumination, or a plurality of apertures of which each central position differ from the optical axis position for modified illumination (in Fig. 1, only two of these aperture stops are shown). The illumination system aperture stop plate 24 is rotated by a driving unit 40 such as a motor, controlled by the main controller 50, and either aperture stop is selectively chosen to be set on the optical path of the exposure light IL in correspondence with the reticle pattern.

[0186]

On the optical path of the exposure light IL outgoing from the illumination system aperture stop plate 24, the beam splitter 26, which has a large transmittance and a small reflectance, is arranged. And further downstream on the optical path, the relay optical system, structured of the first relay lens 28A and the second relay lens 28B is arranged, with the fixed reticle blind 30A and the movable reticle blind 30B arranged in between.

[0187]

The fixed retile blind 30A is arranged on a surface slightly defocused from the conjugate plane relative to the pattern surface of the reticle R, and a rectangular opening is formed to set the illumination area 42R on the reticle R. In addition, close to the fixed retile blind 30A, the movable reticle blind 30B is arranged. The

movable reticle blind 30B has an opening portion, which position and width is variable in the scanning direction, and by further restricting the illumination area 42R via the movable reticle blind 30B during the start and completion of the scanning exposure, exposure on unnecessary portions can be avoided.

[0188]

On the optical path of the exposure light IL further downstream of the second relay lens 28B structuring the relay optical system, the deflection mirror M is arranged to reflect and bend the exposure light IL that has passed through the second relay lens 28 toward the reticle R, and on the optical path beyond the mirror M, the condenser lens 32 is arranged.

[0189]

Furthermore, on either side of the optical path vertically bent at the beam splitter 26 within the illumination optical system 12, an integrator sensor 46 and a reflection light monitor 47 are respectively arranged. As the integrator sensor 46 and the reflection light monitor 47, a silicon PIN type photodiode is used, which is sensitive to light in the far ultraviolet region and the vacuum ultra violet region and also has high response frequency to detect the pulse emission of the light source unit 16. Or, it is possible to use a semiconductor photodetection element having a GaN crystal as the integrator sensor 46 and the reflection light monitor 47.

[0190]

With the structure described above, the incident surface of the fly-eye lens system 22, the arrangement surface of the movable reticle blind 30B, and the pattern surface of the reticle R, are arranged optically conjugated with each other. And, the light source surface formed on the outgoing side of the fly-eye lens system 22 and the Fourier transform surface of the projection optical system PL (exit pupil surface) are arranged optically conjugated with each other, forming a Koehler illumination system.

[0191]

The operation of the illumination optical system 12 having the structure described above will now be briefly described. The laser beam LB, pulse-emitted from the light source unit 16, is incident on the beam shaping optical system 18, and the sectional shape of the laser beam LB is shaped so that it is efficiently incident on the fly-eye lens system 22, which is arranged further downstream. The laser beam LB, is then incident on the fly-eye lens system 22, and the secondary light source is formed on the focal plane of the emitting side of the fly-eye lens system 22 (the pupil surface of the illumination optical system 12). The exposure light IL outgoing from the secondary light source, then passes through one of the aperture stops on the illumination system aperture stop plate 24, and reaches the beam splitter 26, which has a large transmittance and a small

reflectance. The exposure light IL, which passes through the beam splitter 26 proceeds to the first relay lens 28A, and then passes through the rectangular opening of the fixed reticle blind 30A and the movable reticle blind 30B. After passing through the movable reticle blind 30B, the exposure light IL passes through the second relay lens 28B, and the optical path is then bent vertically downward by the mirror M. The exposure light IL, then passes through the condenser lens 32 and illuminates the rectangular illumination are 42R on the reticle R held on the reticle stage RST with a uniform illuminance distribution.

[0192]

Meanwhile, the exposure light IL, which is reflected off the beam splitter 26, passes through the condenser lens 44 and is photo-detected by the integrator sensor 46. And the photoelectric conversion signal of the integrator sensor 46 is sent to the main controller 50 as the output DS (digit/pulse) via a peak hold circuit and an A/D converter (not shown in Figs.). The relative coefficient of the output DS of the integrator sensor 46 and the illuminance (exposure amount) of the exposure light IL on the surface of the wafer W is obtained in advance, and is stored in the memory 51 serving as a storage unit arranged with the main controller 50.

[0193]

In addition, the exposure light, which illuminates the illumination area 42R on the reticle R and is

reflected off the pattern surface of the reticle (the lower surface in Fig. 1), proceeds backward in the opposite direction as before through the condenser lens 32 and the relay lens system, and is reflected off the beam splitter 26 and photo-detected by the reflection light monitor 47 via the condenser lens 48. In addition, in the case the Z tilt stage 58 is arranged below the projection optical system PL, the exposure light IL, which has passed through the pattern surface of the reticle, is reflected off the projection optical system PL and the surface of the wafer W (or the surface of the fiducial mark plate FM, which will be described later), and proceeds backward in the order of the projection optical system PL, the reticle R, the condenser lens 32, and the relay lens system, and is reflected off the beam splitter 26 to be photo-detected by the reflection light monitor 47 via the condenser lens 48. Also, although the surface of each optical element arranged in between the beam splitter 26 and the wafer W has a lens coating to prevent reflection, an extremely small amount of the exposure light IL is reflected on the surface, and the reflection light is also photo-detected by the reflection light monitor 47. The photoconversion signals of the reflection monitor 47 are supplied to the main controller 50 via the peak hold circuit and the A/D converter (not shown in Figs.). The reflection monitor 47 is mainly used to measure the reflectance of the wafer W in the embodiment. The reflection monitor 47 may also be used to

measure the transmittance of the reticle R in advance.

[0194]

As the fly-eye lens system, for example, a double fly-eye lens system, which details are disclosed in Japanese Patent Laid Open No. 01-235289 (the corresponding U.S. Patent No. 5,307,207), and Japanese Patent Laid Open No. 07-142354 (the corresponding U.S. Patent No. 5,534,970), may be employed to structure a Koehler illumination system.

[0195]

In addition, a diffractive optical element may be used with the fly-eye lens system 22. In the case of using such a diffractive optical element, the light source unit 16 and the illumination optical system 12 may be connected with the diffractive optical element arranged in between.

[0196]

That is, in correspondence with each fiber of the bundle-fiber, the diffractive optical element on which the diffractive element is formed can be arranged in the beam shaping optical system 18, and the laser beam emitted from each fiber can be diffracted so that the beams are superimposed on the incident surface of the fly-eye lens system 22. In the embodiment, the output end of the bundle-fiber may be arranged on the pupil surface of the illumination optical system. In this case, however, the intensity distribution (in other words, the shape and size of the secondary light source) on the pupil surface

varies due to the first function (partial on/off to reduce total output), and may not be the most suitable shape and size for the reticle pattern. Thus, it is preferable to use the diffractive optical element and the like described earlier, to superimpose the laser beam from each fiber on the pupil surface of the illumination optical system or on the incident surface of the optical integrator.

[0197]

In any case, in the embodiment, even if the distribution of the portion that emits light from the bundle-fiber 173 varies, uniform illuminance distribution on both the pattern surface (object surface) of the reticle R and the surface (image plane) of the wafer W can be sufficiently secured due to the first function of the light amount controller 16C, referred to earlier.

[0198]

The reticle R is mounted on the reticle stage RST, and is held on the stage by vacuum chucking (not shown in Figs.). The reticle stage RST is finely drivable within a horizontal surface (XY plane), as well as scanned in the scanning direction (in this case, the Y direction, being the landscape direction in Fig. 1) within a predetermined stroke range by the reticle stage driving portion 49. The position and rotational amount of the reticle stage RST during scanning, is measured via the movable mirror 52R fixed to the reticle stage RST by the laser interferometer 54R arranged externally, and the

measurement values of the laser interferometer 54R is supplied to the main controller 50.

[0199]

The material used for the reticle R depends on the wavelength of the exposure light IL. That is, in the case of using exposure light with the wavelength of 193nm, synthetic quartz can be used. In the case of using exposure light with the wavelength of 157nm, however, the reticle R needs to be made of fluorite, fluorine-doped synthetic quartz, or crystal.

[0200]

The projection optical system PL is, for example, a double telecentric reduction system, and is made up of a plurality of lens elements 70a, 70b, ……, which have a common optical axis in the Z-axis direction. In addition, as the projection optical system PL, a projection optical system having a projection magnification β of, for example, 1/4, 1/5, or 1/6, is used. Therefore, when the illumination area 42R on the reticle R is illuminated with the exposure light IL as is described earlier, the pattern formed on the reticle R is projected and transferred as a reduced image by the projection magnification β with the projection optical system PL on the slit-shaped exposure area 42W on the wafer W, which surface is coated with the resist (photosensitive agent).

[0201]

In the embodiment, of the lens elements referred to above, a plurality of lens elements are respectively

capable of moving independently. For example, the lens element 70a arranged topmost and closest to the reticle stage RST is held by a ring-shaped supporting member 72, and this ring-shaped supporting member 72 is supported at three points by expandable driving elements such as piezo elements 74a, 74b, and 74c (74c in depth of the drawing is not shown in Fig. 1), and is also connected to the barrel portion 76. The three points on the periphery of the lens element 70a is movable independently in the optical axis direction AX of the projection optical system PL by the driving elements 74a, 74b, and 74c. That is, translation operation of the lens element 70a can be performed along the optical axis AX in accordance with the deviation amount of the driving elements 74a, 74b, and 74c, as well as tilt operation of the lens element 70a in respect to the plane perpendicular to the optical axis AX. And the voltage provided to the driving elements 74a, 74b, and 74c is controlled by the image forming characteristics correction controller 78 based on instructions from the main controller 50, and thus the deviation amount of the driving elements 74a, 74b, and 74c is controlled. Also, in Fig. 1, the optical axis AX of the projection optical system PL refers to the optical axis of the lens element 70b and the other lens elements (omitted in Fig. 1) fixed to the barrel portion 76.

[0202]

In addition, in the embodiment, the relation between the vertical movement amount of the lens element 70a and

the variation in magnification (or in distortion) is obtained in advance by experiment. The relation, for example, is stored in a memory within the main controller 50, and the magnification (or distortion) correction is performed by calculating the vertical movement amount of the lens element 70a from the magnification (or distortion) corrected by the main controller 50 on correction, and by providing instructions to the image forming characteristics correction controller 78 to drive the driving elements 74a, 74b, and 74c to correct the magnification (or distortion). That is, in the embodiment, the image forming characteristics correction controller 78, the driving elements 74a, 74b, and 74c, and the main controller 50 make up the image forming characteristics correction unit, which corrects the image forming characteristics of the projection optical system PL.

[0203]

Further, optical calculation values can be used in the relation between the vertical movement amount of the lens element 70a and the variation in magnification. In this case, the experimental process to obtain the relation between the vertical movement amount of the lens element 70a and the variation in magnification can be omitted.

[0204]

As is described earlier, the lens element 70a closest to the reticle R is movable. The lens element 70a is selected, because the influence on the magnification and

distortion characteristics is greater compared with the other lens elements, however, any lens element may be arranged movable alternately of the lens element 70a to adjust the interval between lenses, if identical conditions can be satisfied.

[0205]

Also, by moving at least one optical element besides the lens element 70a, other optical properties such as the field curvature, astigmatism, coma, and spherical aberration can be adjusted. Moreover, a sealed chamber may be arranged in between specific lens elements near the center in the optical axis direction of the projection optical system PL, and an image forming characteristics correction mechanism can be arranged to adjust the magnification of the projection optical system PL by adjusting the pressure of the gas inside the sealed chamber with a pressure adjustment mechanism such as a bellows pump. Or, alternately, for example, an aspherical lens may be used as a part of the lens element structuring the projection optical system PL, and the aspherical lens may be rotated. In this case, correction of the so-called rhombic distortion becomes possible. Or, the image forming characteristics correction mechanism may have the structure of a plane-parallel plate arranged within the projection optical system PL, which can be tilted and rotated.

[0206]

Furthermore, in the case of using the laser beam with

the wavelength of 193m as the exposure light IL, materials such as synthetic quartz and fluorite can be used for each lens element (and the plane-parallel plate) structuring the projection optical system PL. In the case of using the laser beam with the wavelength of 157nm, however, only fluorite is used as the material for the lenses and the like.

[0207]

In addition, in the embodiment, an environmental sensor 77 is arranged to measure at least the atmospheric pressure in the chamber 11. The measurement values of the environmental sensor 77 is sent to the main controller 50, and the main controller 50 calculates the change in pressure from the standard atmospheric pressure as well as calculates the atmospheric change of image forming characteristics in the projection optical system PL, based on the measurement values of the environmental sensor 77. And, the main controller 50 gives instructions to the image forming characteristics correction controller 78 in consideration of this atmospheric variation, and corrects the image forming characteristics of the projection optical system PL.

[0208]

Since the calculation method of the atmospheric pressure variation, the illumination variation, and the like performed by the main controller 50 is disclosed in detail, for example, in Japanese Patent Laid Open No. 09-213619 and is well acknowledged, a detailed description

will therefore be omitted.

[0209]

The XY stage 14 is driven two-dimensionally, in the Y direction, which is the scanning direction, and in the X direction, which is perpendicular to the Y direction (the direction perpendicular to the page surface of Fig. 1), by the wafer stage driving portion 56. The Z tilt stage 58 is mounted on the XY stage 14, and on the Z tilt stage 58, the wafer W is held via a wafer holder (not shown in Figs.) by vacuum chucking and the like. The Z tilt stage 58 has the function of adjusting the position of the wafer W in the Z direction by for example, three actuators (piezo elements or voice coil motors), and also the function of adjusting the tilting angle of the wafer W in respect to the XY plane (image plane of the projection optical system PL). In addition, the position of the XY stage 14 is measured via the movable mirror 52W fixed on the Z tilt stage 58 by the laser interferometer 54W, which is externally arranged, and the measurement values of the laser interferometer 54W is sent to the main controller 50.

[0210]

As the movable mirror, in actual, an X movable mirror that has a reflection plane perpendicular to the X-axis and a Y movable mirror that has a reflection plane perpendicular to the Y-axis are arranged, and in correspondence with these mirrors, interferometers for an X-axis position measurement, Y-axis position measurement,

and rotation (including yawing amount, pitching amount, and rolling amount) measurement are respectively arranged. In Fig. 1, however, these are representatively shown as the movable mirror 52W and the laser interferometer 54W.

[0211]

In addition, on the Z tilt stage 58 close to the wafer W, an irradiation amount monitor 59, which has a photo-detecting surface arranged at the same height as that of the exposure surface on the wafer W, is arranged to detect the light amount of the exposure light IL that has passed through the projection optical system PL. The irradiation amount monitor 59 has a housing that is one size larger than the exposure area 42W, extends in the X direction, and is rectangular in a planar view. And in the center portion of this housing, an opening is formed, which has a slit-shape almost identical to the exposure area 42W. This opening is actually made by removing a portion of a light shielding film formed on the upper surface of the photo-detection glass made of materials such as synthetic quartz, which forms the ceiling surface of the housing. And, immediately below the opening via the lens, an optical sensor having a photodetection element such as the silicon PIN type photodiode is arranged.

[0212]

The irradiation amount monitor 59 is used to measure the intensity of the exposure light IL irradiated on the exposure area 42W. The light amount signals according to

the amount of light received by the photodetection element structuring the irradiation amount monitor 59 is sent to the main controller 50.

[0213]

The optical sensor does not necessarily have to be arranged within the Z tilt stage 58, and it is a matter of course that the optical sensor may be arranged exterior to the Z tilt stage 58. In this case, the illumination beam relayed by the relay optical system may be guided to the optical sensor via an optical fiber or the like.

[0214]

On the Z tilt stage 58, the fiducial mark plate FM used when performing operations such as reticle alignment, which will be described later, is arranged. The fiducial mark plate FM is arranged so that the height of the surface is almost the same as that of the surface of the wafer W. On the surface of the fiducial mark plate FM, fiducial marks for reticle alignment, baseline measurement, and the like, are formed.

[0215]

Also, it is omitted in Fig. 1 to avoid complication in the drawing, in actual, the exposure apparatus 10 comprises a reticle alignment system to perform reticle alignment.

[0216]

When alignment is performed on the reticle R, first of all, the main controller 50 drives the reticle stage

RST and the XY stage 14 via the reticle stage driving portion 49 and the wafer stage driving portion 56 so that the fiducial mark for reticle alignment on the fiducial mark plate FM is set within the exposure area 42W having a rectangular shape and the positional relationship between the reticle R and the Z tilt stage 58 is set so that the reticle mark image on the reticle R almost overlaps the fiducial mark. In this state, the main controller 50 picks up the image of both marks using the reticle alignment system, processes the pick-up signals, and calculates the positional shift amount of the projected image of the reticle mark in respect to the corresponding fiducial mark in the X direction and the Y direction.

[0217]

In addition, it is also possible to obtain the focus offset and leveling offset (the focal position of the projection optical system PL, image plane tilt, and the like) based on information on contrast, which is included in the detection signals (picture signals) of the projected image of the fiducial marks obtained as a consequence of the reticle alignment described above.

[0218]

Also, in the embodiment, when the reticle alignment is performed, the main controller 50 also performs baseline measurement of the off-axis alignment sensor on the wafer side (not shown in Figs.) arranged on the side surface of the projection optical system PL. That is, on

the fiducial mark plate FM, fiducial marks for baseline measurement that are arranged in a predetermined positional relationship in respect to the fiducial marks for reticle alignment are formed. And when the positional shift amount of the reticle mark is measured via the reticle alignment system, the baseline amount of the alignment sensor, in other words, the positional relationship between the reticle projection position and the alignment sensor, is measured by measuring the positional shift of the fiducial marks for baseline measurement in respect to the detection center of the alignment sensor via the alignment sensor on the wafer side.

[0219]

Furthermore, as is shown in Fig. 1, with the exposure apparatus 10 in the embodiment, it has a light source which on/off is controlled by the main controller 50, and a multiple focal position detection system (a focus sensor) based on the oblique incident method is arranged, consisting of an irradiation optical system 60a which irradiates light from an incident direction in respect to the optical axis AX to form multiple pinhole or slit images toward the image forming plane of the projection optical system PL, and of an photodetection optical system 60b which photo-detects the light reflected off the surface of the wafer W. By controlling the tilt of the plane-parallel plate arranged within the photodetection optical system 60b (not shown in Figs.) in

respect to the optical axis of the reflected light, the main controller 50 provides an offset corresponding to the focal change of the projection optical system PL to the focal detection system (60a, 60b) and performs calibration. With this operation, the image plane of the projection optical system PL within the exposure area 42W coincides with the surface of the wafer W within the range (width) of the depth of focus. Details on the structure of the multiple focal position detection system (a focus sensor) similar to the one used in the embodiment, are disclosed in, for example, Japanese Patent Laid Open No. 06-283403.

[0220]

The main controller 50 performs automatic focusing and automatic leveling by controlling the Z position of the Z tilt stage 58 via the driving system (not shown in Figs.) so that the defocus becomes zero, based on the defocus signals such as the S-curve signals from the photodetection optical system 60b.

[0221]

The reason for arranging the plane-parallel plate within the photodetection optical system 60b to provide an offset to the focal detection system (60a, 60b) is, for example, that when the lens element 70a is vertically moved for magnification correction the focus also changes, and when the projection optical system PL absorbs the exposure light IL the position of the image forming plane changes with the change in the image forming

characteristics of the projection optical system PL, and accordingly, it is necessary in such cases to make the focusing position of the focal detection system coincide with the position of the image forming plane of the projection optical system PL by providing an offset to the focal detection system. Therefore, in the embodiment, the relationship between the vertical movement amount of the lens element 70a and the focus variation is also obtained in advance by experiment, and is stored in the memory within the main controller 50. Calculated values may be used for the relationship between the vertical movement amount of the lens element 70a and the focus variation. And, as for the automatic leveling, it may be performed only in the non-scanning direction, which is perpendicular to the scanning direction, without being performed in the scanning direction.

[0222]

The main controller 50 is structured including a so-called microcomputer (or workstation) made up of components such as a CPU (central processing unit), a ROM (Read Only Memory), a RAM (Random Access Memory), and the like. Other than performing various controls described so far, the main controller 50 controls, for example, the synchronous scanning of the reticle R and the wafer W, the stepping operation of the wafer W, the exposure timing, and the like so that the exposure operation is performed accurately. In addition, in the embodiment, the main controller 50 has control over the whole apparatus,

besides controls such as controlling the exposure amount on scanning exposure as will be described later, and calculating the variation amount of the image forming characteristics of the projection optical system PL and adjusting the image forming characteristics of the projection optical system PL based on the calculation via the image forming characteristics correction controller 78.

[0223]

To be more precise, for example, on scanning exposure, the main controller 50 respectively controls the position and velocity of the reticle stage RST and the XY stage 14 via the reticle stage driving portion 49 and the wafer stage driving portion 56 so that the wafer W is scanned via the XY stage 14 at the velocity $V_W=\beta\cdot V$ (β is the projection magnification from the reticle R to the wafer W) in the -Y direction (or +Y direction) in respect to the exposure area 42W, in synchronous with the reticle R scanned via the reticle stage RST at the velocity $V_R=V$ in the +Y direction (or -Y direction), based on the measurement values of the laser interferometers 54R and 54W. Also, when performing stepping operations, the main controller 50 controls the position of the XY stage 14 via the wafer stage driving portion 56, based on the measurement values of the laser interferometer 54W.

[0224]

The exposure sequence of the exposure apparatus 10 in the embodiment will be described next, when exposure on

predetermined slices (N slices) of wafers W is performed to transfer the reticle pattern onto the wafer W, while mainly referring to the controls performed by the main controller 50.

[0225]

The premise is as follows:

① A shot map data (data deciding the exposure sequence of each shot area and the scanning direction) is made and stored in the memory 51 (refer to Fig. 1), based on necessary data such as the shot arrangement, size of shot, and exposure sequence of each shot, which are input by the operator through an input/output device 62 (refer to Fig. 1) such as a console.

② In addition, the output of the integrator sensor 46 is calibrated in advance in respect to the output of the reference illuminometer (not shown in Figs.) that is arranged on the Z tilt stage 58 at the same height as of the image plane (that is, the surface of the wafer W). The calibration of the integrator sensor 46, in this case, means to obtain the conversion coefficient (or conversion function) to convert the output of the integrator sensor 46 to the exposure amount on the image plane. By using this conversion coefficient, measuring the exposure amount (energy) indirectly provided on the image plane by the output of the integrator sensor 46 becomes possible.

③ In addition, the output of: the energy monitor within the beam monitor mechanism 164; the photoconversion elements 180, 181 within the light amplifying portion

161; and the photoconversion element 182 within the wavelength conversion portion 163, and the like are calibrated in respect to the output of the integrator sensor 46 that has already been calibrated. The relative coefficient of the output of the respective sensors in respect to the output of the integrator sensor 46 is also obtained in advance, and stored in the memory 51.

④ Furthermore, in respect to the output of the integrator sensor 46 which has completed calibration, the output of the reflection light monitor 47 is calibrated. The relative coefficient of the output of the reflection light monitor 47 in respect to the output of the integrator sensor 46 is obtained in advance, and stored in the memory 51.

[0226]

First of all, the operator inputs the exposure conditions including the illumination conditions (the numerical aperture of the projection optical system, the shape of the secondary light source (the type of aperture stop 24), the coherence factor σ and the type of reticle pattern (such as contact hole, line and space), the type of reticle (such as phase contrast reticle, half-tone reticle), and the minimum line width or the exposure amount permissible error) from the input/output device 62 (refer to Fig. 1) such as the console. According to the input, the main controller 50 sets the aperture stop (not shown in Figs.) of the projection optical system PL, selects and sets the aperture stop of the illumination

system aperture stop plate 24, and sets the target exposure amount (which corresponds to the set light amount) in accordance with the resist sensitivity, and the like. While these are being performed, at the same time, the main controller 50 selects the channels to be turned on/off at the bundle-fiber 173 output so that the light amount emitted from the light source unit 16 in order to obtain the target exposure amount almost coincides with the set light amount, and gives instructions to the light amount controller 16C to select the specific channels. With this operation, on scanning exposure, which will be described later, the light amount controller 16C performs the on/off operation of the fiber amplifier 171_n of each channel almost simultaneously with the emission of the laser light source 160A, based on the first function in accordance with the selection instructions. Thus, rough adjustment of the exposure amount is performed.

[0227]

Next, the main controller 50 loads the reticle R subject to exposure on the reticle stage RST, using the reticle loader (not shown in Figs.).

[0228]

Then, the reticle alignment described earlier is performed, using the reticle alignment system, as well as the baseline measurement.

[0229]

And then, the main controller 50 instructs the wafer

carriage system (not shown in Figs.) to exchange the wafer W. By the instructions, the wafer is exchanged (or simply loaded when there are no wafers on the stage) by the wafer carriage system and the wafer delivery mechanism (not shown in Figs.) on the XY stage 14. When this is completed, a series of operations in the alignment process are performed, such as the so-called search alignment and fine alignment (EGA and the like). Because the wafer exchange and the wafer alignment are performed likewise, as is performed with the well-acknowledged exposure apparatus, more detailed description is omitted here.

[0230]

Next, based on the above alignment results and the shot map data, the reticle pattern is transferred onto a plurality of shot areas on the wafer W based on the step-and-scan method by repeatedly performing the operation of moving the wafer W to the starting position for scanning to expose each shot area on the wafer W and the scanning exposure operation. During this scanning exposure, in order to provide the target exposure amount to the wafer W, which is decided in accordance with exposure conditions and the resist sensitivity, the main controller 50 gives instructions to the light amount controller 16C while monitoring the output of the integrator sensor 46. And according to the instructions, in addition to the rough adjustment of the exposure amount based on the first function, the light amount

controller 16C controls the frequency and the peak power of the laser beam (pulse ultraviolet light) from the light source unit 16 based on the second and third functions, thus performs fine adjustment of the exposure amount.

[0231]

In addition, the main controller 50 controls the illumination system aperture stop plate 24 via the driving unit 40, and furthermore, controls the opening/closing of the movable reticle blind 30B in synchronous with the operation information of the stage system.

[0232]

When exposure on the first wafer W is completed, the main controller 50 instructs the wafer carriage system (not shown in Figs.) to exchange the wafer W. Wafer exchange is thus performed, by the wafer carriage system and the wafer delivery mechanism (not shown in Figs.) on the XY stage 14, and after the wafer exchange is completed, search alignment and fine alignment is performed likewise as is described above to the wafer that has been exchanged. In addition, in this case, the main controller 50 calculates the irradiation change of the image forming characteristics (including the change in focus) of the projection optical system PL from the start of exposure on the first wafer W, based on the measurement values of the integrator sensor 46 and the reflection light monitor 47. The main controller 50 then

provides instruction values to the image forming characteristics correction controller 78 to correct the irradiation change, as well as provides an offset to the photodetection optical system 60b. Also, the main controller 50 calculates the environmental change such as the atmospheric pressure change of the image forming characteristics of the projection optical system PL based on the measurement values of the environmental sensor 77, and provides instruction values to the image forming characteristics correction controller 78 to correct the irradiation change, as well as provides an offset to the photodetection optical system 60b.

[0233]

And, in the manner described earlier, the reticle pattern is transferred onto the plurality of shot areas on the wafer W based on the step-and-scan method. When exposure on the second wafer is completed, hereinafter, the wafer exchange and exposure based on the step-and-scan method are repeatedly performed in sequence, likewise as above.

[0234]

When exposure is performed on the wafer W, on N slices of wafers, the main controller 50 performs feedback control via the laser controller 16B based on the monitoring results of the beam monitor mechanism 164, in order to stably maintain the oscillation wavelength of the laser light source 160A at the set wavelength. Therefore, generation or change in aberration (image

forming characteristics) of the projection optical system PL due to the change in wavelength is prevented, and the image characteristics (optical properties such as image quality) do not change during the transfer of the pattern.

[0235]

Meanwhile, instead of driving the driving elements 74a, 74b, and 74c to correct the environmental change including the atmospheric pressure change of the projection optical system PL referred to above by providing instructions to the image forming characteristics correction controller 44, the main controller 50 may obtain the change in pressure, temperature, and humidity from the standard state based on the measurement values of the environmental sensor 77 at every predetermined timing since exposure on the first wafer W has started, and calculate the amount of wavelength change to almost cancel out the environmental change of the image forming characteristics of the projection optical system PL due to the change in pressure, temperature, and humidity. And, according to the amount of wavelength change calculated, the main controller 50 may positively change the oscillation wavelength of the laser light source 160A.

[0236]

Such change in the oscillation wavelength, can be easily performed by the laser controller 16B positively controlling the temperature of the etalton element structuring the beam monitor mechanism 164 based on

instructions from the main controller 50 and changing the set wavelength (target wavelength) that coincides with the resonance wavelength (detection reference wavelength) maximizing the transmittance of the etalon element, as well as by performing feedback control on the temperature of the DFB semiconductor laser 160A so that the oscillation wavelength of the DFB semiconductor laser 160A coincides with the set wavelength that has been changed.

[0237]

In this manner, the change in aberration, projection magnification, and image characteristics such as the focal position in the projection optical apparatus PL due to the change in atmospheric pressure, temperature, humidity and the like can be cancelled out at the same time while the exposure apparatus 10 is operating. That is, by changing of the oscillation wavelength of the DFB semiconductor laser 160A, a state can be created as if there were no environmental change from the standard state (that is, a state where the variation amount in optical performance is cancelled out).

[0238]

Such wavelength change, or to be more concrete, change in set wavelength and the stabilizing control of the oscillation wavelength of the laser light source 160A having the changed set wavelength as the reference, are performed in the following cases.

[0239]

For example, when focusing on the atmospheric pressure, normally, the standard atmospheric pressure is often set at the average atmospheric pressure of the delivery place (such as factories) where the exposure apparatus is arranged. Accordingly, when there is an altitude difference between the places where the exposure apparatus is built and where the exposure apparatus will be arranged (delivered), for example, adjustment of the projection optical system and the like are performed at the place where the exposure apparatus is built by shifting the exposure wavelength by only the amount corresponding to the altitude difference as if the projection optical system were arranged under the standard atmospheric pressure (average atmospheric pressure), and adjusting the wavelength back to the exposure wavelength at the place where the exposure apparatus will be arranged. Or the adjustment of the projection optical system is performed at the place where the exposure apparatus is built with the exposure wavelength, and the exposure wavelength is shifted at the place where the exposure apparatus will be arranged so as to cancel out the altitude difference. The same can be said for other environmental conditions, that is, also for temperature, humidity, and the like. With these operations, the change in image forming characteristics (such as aberration) of the projection optical system PL due to the altitude difference, pressure difference, and furthermore, the environmental difference (the atmosphere

within the clean room) between the building place and the delivery place of the exposure apparatus can be cancelled out, and it becomes possible to reduce the start-up time required at the delivery place. Furthermore, the change in aberration, projection magnification, and focal position in the projection optical system PL due to the atmospheric pressure change during the operation of the exposure apparatus can be cancelled out, and it becomes possible to transfer the pattern image onto the substrate in the best image forming state at all times.

[0240]

As can be seen, the embodiment uses the fact that changing the wavelength of the illumination light with the projection optical system and changing the set environment (the pressure, temperature, humidity and the like of the surrounding gas) of the projection optical system are substantially equivalent. When the refraction element of the projection optical system is made of a single material, then the equivalence is complete, and in the case a plurality of materials are used, the equivalence is almost complete. Accordingly, by using the variation characteristics of the refractive index of the projection optical system (especially the refraction element) in respect to the set environment and changing only the wavelength of the illumination light, an equivalent state of when the set environment of the projection optical system has been changed can be substantially created.

[0241]

The standard atmospheric pressure may be arbitrary, however, for example, it is preferable for it to be the reference atmospheric pressure when adjustment of the projection optical system and the like are performed to optimize the optical properties. In this case, at the standard atmospheric pressure, the variation amount of the optical properties of the projection optical system and the like is null.

[0242]

In addition, when the projection optical system PL is to be arranged in an atmosphere other than air, the atmospheric pressure is the pressure of the surrounding atmosphere (gas) of the projection optical system PL. That is, in this description, atmospheric pressure is used in a broader sense than the usual sense meaning the pressure of atmosphere (air), and includes the pressure of the surrounding atmosphere (gas).

[0243]

In the case the environmental change in the image forming characteristics of the projection optical system PL cannot be cancelled out by changing the wavelength in the manner described above, each time the set wavelength is changed the main controller 50 corrects the image forming characteristics change excluding the environmental change of the projection optical system PL that is corrected by changing the set wavelength, by driving the driving elements 74a, 74b, and 74c via the

image forming characteristics correction controller 78. With this operation, a large part of the environmental change in the image forming characteristics of the projection optical system PL is corrected by the change in set wavelength described above, and the remaining environmental change, irradiation change, and the like of the projection optical system PL are corrected by driving the driving elements 74a, 74b, and 74c with the image forming characteristics correction controller 78. As a consequence, exposure with high precision is performed in a state where the image forming characteristics of the projection optical system PL is almost completely corrected.

[0244]

Furthermore, in between the change in set wavelength described earlier, the main controller 50 may correct the image forming characteristics change with consideration of the environmental change. The change in set wavelength is performed at the predetermined timing described previously, however, when the interval between the change in set wavelength is long, the pressure, temperature, humidity, and the like changes during the interval. In such a case, however, the change in image forming characteristics of the projection optical system due to these changes can be corrected with the arrangement above.

[0245]

The predetermined timing, here, may be each time when exposure on the wafer W has been completed in

predetermined slices, or may be each time when exposure on each shot area on the wafer W has been completed. The predetermined slices may be one slice of wafer, or it may be the slices of wafers equivalent to one lot.

[0246]

Or, the predetermined timing may be each time when the exposure conditions are changed. In addition, when the exposure conditions are changed, other than the change in illumination conditions, this change includes all the cases when conditions such as reticle exchange, which are related to exposure in a broad sense, are changed. For example, if the wavelength is changed in parallel with the reticle exchange during the so-called double exposure and the illumination system aperture stop change, reduction in throughput can be prevented since hardly any time is wasted.

[0247]

Or, the predetermined timing may be the time when the change in physical quantity such as the atmospheric pressure obtained based on the measurement values of the environmental sensor 77 exceeds a predetermined amount. Or, the predetermined timing may be almost realtime, corresponding to the interval calculating the optical performance of the projection optical system PL (for example, several μs). Or, the predetermined timing may be every predetermined timing set in advance.

[0248]

Furthermore, it is possible to cope with the

correction including the correction of the irradiation change by changing the wavelength of the laser beam. In this case, it is preferable to make an irradiation change model of a plurality of typical wavelengths respectively, by experiment or by simulation. If the changed wavelength is in between the wavelengths of the irradiation change model, for example, the image forming characteristics or the variation amount is preferably obtained by interpolation calculation.

[0249]

In addition, the sensitivity properties of the resist (photosensitive agent) coated on the wafer W may change due to the wavelength shift. In this case, the main controller 50 preferably controls the exposure amount by changing the exposure parameter, which will be described later, according to the change in the sensitivity properties, that is changing at least either the scanning velocity, the width of the illumination area, the intensity of the illumination light, or the oscillation frequency. It is preferable to obtain the sensitivity properties of the resist corresponding to the plurality of typical wavelengths by experiment or by simulation, moreover, in the case the changed wavelength is in between the wavelengths of the obtained sensitive properties, for example, the sensitive properties of the wavelength is preferably obtained by interpolation calculation.

[0250]

The rough adjustment of the exposure amount (light amount) described earlier may be precisely controlled in the accuracy of 1% and under to the exposure amount set value, by performing test emission prior to the actual exposure.

[0251]

The dynamic range of the rough adjustment of the exposure amount in the embodiment can be set within the range of 1 - 1/128. The dynamic range normally required, however, is around 1 - 1/7 in typical, therefore, the number of channels (the number of optical fibers) which light output should be turned on may be controlled in between 128 - 18. In this manner, in the embodiment, rough adjustment of the exposure amount in line with the difference of the resist sensitivity and the like of each wafer can be accurately performed by the exposure amount control individually turning on/off the light output of each channel.

[0252]

Accordingly, with the embodiment, the rough energy adjuster such as the ND filter used in the conventional excimer laser exposure apparatus is not necessary.

[0253]

In addition, since the light amount control based on the second and third function by the light amount controller 16C has the features of quick control velocity and high control accuracy, it is possible to satisfy the following control requirements required in the current

exposure apparatus without fail.

[0254]

That is, the light amount control satisfies all of: the dynamic range being around ±10% of the set exposure amount, which is a requirement for exposure amount control correcting the process variation of each shot area (chip) on the same wafer caused due to uneven resist film thickness within the same wafer; controlling the light amount to the set value within around 100ms, which is the stepping time in between shots; control accuracy of around ±1% of the set exposure amount; setting the light amount to ±0.2% of the set exposure amount within 20msec, which is the typical exposure time for one shot area as the exposure accuracy, being a requirement for exposure control to achieve line width uniformity within a shot area; and the control velocity of around 1ms.

[0255]

Accordingly, for light amount control, the light amount controller 16C only has to perform light amount control based on at least either the second function or the third function.

[0256]

In addition, with the scanning exposure apparatus that has a laser light source (pulse light source) as in the exposure apparatus 10 of the embodiment, when the scanning velocity of the wafer W is V_W, the width of the slit shaped exposure area 42W on the wafer W in the scanning direction (slit width) is D, and the pulse

repetition frequency of the laser light source is F, the distance in which the wafer W moves in between pulse emission is V_W/F, thus the number of pulse (the number of exposure pulse) N of the exposure light IL to be irradiated at one point on the wafer is expressed as in the following equation (3).

[0257]

$N=D/(V_W/F)$ ······(3)

[0258]

When the pulse energy is expressed as P, the energy that is to be provided at one point on the wafer for a unit time is expressed as in the following equation (4).

[0259]

$E=NP=ND/(V_W/F)$ ······(4)

[0260]

Accordingly, with the scanning exposure apparatus, exposure amount control is possible by controlling either the slit width D, the scanning velocity V_W, the pulse repetition frequency F of the laser light source, or the pulse energy P. Due to the problem of response velocity, since it is difficult to adjust the slit width D during scanning exposure, either the scanning velocity V_W, the pulse repetition frequency F of the laser light source, or the pulse energy P may be adjusted.

[0261]

Therefore, with the exposure apparatus 10 in the embodiment, as a matter of course, the exposure amount control can be performed by combining the light amount

control based on either the second or third function by the light amount controller 16C and the scanning velocity.

[0262]

For example, the exposure conditions of the wafer W is changed in accordance with the reticle pattern to be transferred onto the wafer W, such as changing the intensity distribution of the illumination light (that is, the shape and size of the secondary light source) on the pupil surface of the illumination optical system, or inserting/removing the optical filter which shields the circular area having the optical axis as its center around the pupil surface of the projection optical system PL. The illuminance on the wafer W changes by these changes in exposure conditions, however, the illuminance on the wafer W also changes with the change in the reticle pattern. This is due to the difference in the occupied area by the shielding area (or the transmitting area) of the pattern. Therefore, when the illuminance changes due to the change of at least either the exposure conditions or the reticle pattern, it is preferable to control at least either the frequency or the peak power referred to above so as to provide the suitable exposure amount to the wafer (resist). On this control, in addition to adjusting at least either the frequency or the peak power, the scanning velocity of the reticle and the wafer may also be adjusted.

[0263]

As is obvious from the description so far, in the

embodiment, the main controller 50 plays the part of the first controller, the second controller, and the third controller. These controllers can, of course, be structured separately with different controllers.

[0264]

As described so far, with the light source unit 16 related to the embodiment, the temperature dependence of the detection reference wavelength (resonance wavelength) of the wavelength detection unit (more precisely, the etalon element within the beam monitor mechanism 164) which detects a wavelength of a laser beam is measured beforehand along with the temperature dependence of the oscillation wavelength of the DFB semiconductor laser 16B, and a temperature dependence amp made up of theses data is stored in a memory. And, the main controller 50 performs an absolute wavelength calibration to make the detection reference wavelength of the beam monitor mechanism 164 (the resonance wavelength of the etalon element) almost coincide with an absolute wavelength provided by an absorption cell 165, and also performs a set wavelength calibration to make the detection reference wavelength coincident with a set wavelength based on the temperature dependence map. In this manner, with the light source unit of the present embodiment, the set wavelength calibration is performed to make the detection reference wavelength of the beam monitor mechanism 164, on which the absolute wavelength calibration has been performed, coincide with the set

wavelength, using the temperature dependence map including the known temperature dependence data of the detection reference wavelength of the beam monitor mechanism 164. Therefore, the detection reference wavelength of the beam monitor mechanism 164 can be accurately set to the set wavelength at all times without fail, and as a consequence, a wavelength stabilizing control which securely maintains the center wavelength of the laser beam at a predetermined set wavelength using the beam monitor mechanism 164 becomes possible, without being affected by changes in the atmosphere of the beam monitor mechanism 164, such as the temperature.

[0265]

Further, the main controller 50 performs the absolute wavelength calibration and set wavelength calibration of the detection reference wavelength by controlling the temperature of the etalon element (a Fabry-Perot etalon) structuring the beam monitor mechanism 164 via the laser controller 16B, and therefore it becomes possible to set the detection reference wavelength to the set wavelength utilizing the temperature dependence of the resonance wavelength, which is the base of the wavelength detection of the etalon element.

[0266]

In addition, because the main controller 50 performs wavelength control of the laser light source 160A via the laser controller 16B together when performing the absolute wavelength calibration, the absolute wavelength

calibration can be completed within a shorter period of time compared with the case when wavelength control of the laser beam is not performed. However, the wavelength control of the laser light source 160A does not always have to be performed when performing the absolute wavelength calibration.

[0267]

Further, the main controller 50 feedback controls a wavelength of the laser beam from the laser light source 160A via the laser controller 16B after the set wavelength calibration is completed, based on monitoring results of the beam monitor mechanism 164 which has completed the set wavelength calibration. Therefore, the main controller 50 controls the wavelength of the laser beam emitted from the laser light source 160A via the laser controller 16B based on the monitoring results of the beam monitor mechanism 164 which detection reference wavelength is accurately set to the set wavelength, and accordingly the wavelength of the laser beam can be stably maintained at the set wavelength.

[0268]

Since the light source unit 16 related to the embodiment comprises a light amplifying portion 161 including fiber amplifiers 168_n and 171_n which amplify a laser beam from the laser light source 160A, these fiber amplifiers can amplify the laser beam from the laser light source 160A. Therefore, even when a solid-state laser such as the compact DFM semiconductor laser and the

fiber laser is used as the laser light source 160A, the intensity of an output light can be set sufficiently higher. In addition, the light source unit 160 comprises a wavelength conversion portion 163 which includes a nonlinear optical crystal to convert a wavelength of the amplified laser beam, and can generate the eighth harmonic wave having the wavelength of 193nm which is the same wavelength as the ArF excimer laser or the tenth harmonic wave having the same wavelength as the F_2 laser, by converting the wavelength of the laser beam having the wavelength of around 1.5μm generated from the light amplifying portion 161, with the wavelength conversion portion 163. Accordingly, a compact, lightweight and excellent light source unit, which emits a high power energy beam having a short wavelength, is realized by the light source unit 160.

[0269]

Further, because the light source unit 16 related to the embodiment comprises a branch and delay portion 167 which individually delays light output from each of a plurality of optical path so as to stagger the light output temporally, the light is not emitted from each optical path at the same time. Consequently, the light emitted from the light source unit 16 does not temporally overlap with each other while being an extremely narrow-banded light having a single wavelength, and therefore, the spatial coherency between each channel output can be reduced.

[0270]

With the exposure apparatus 10 related to the embodiment, the main controller 50 performs the absolute wavelength calibration previously described and the set wavelength calibration that follows the absolute wavelength calibration prior to exposure. And during exposure, the main controller 50 feedback controls the temperature and current of the laser light source 160A via the laser controller 16B, based on the monitoring results of the beam monitor mechanism which set wavelength calibration has been completed. That is, the main controller 50 transfers the pattern of the reticle R onto the wafer W via the projection optical system PL by irradiating the laser beam on the reticle R, while performing wavelength stabilizing control to maintain the center wavelength of the laser beam to the predetermined set wavelength without fail, based on the monitoring results of the beam monitor mechanism 164 that has completed the set wavelength calibration. Thus, exposure with high precision, which is hardly influenced by the temperature change and the like of the atmosphere, becomes possible.

[0271]

In addition, with the exposure apparatus 10, at each predetermined timing after the exposure on the wafer W begins, the main controller 50 calculates the amount of wavelength change to almost cancel out the change in image forming characteristics of the projection optical

system PL caused by the change in environment (pressure, temperature, humidity, and the like) from the standard state, based on the measurement values of the environmental sensor 77, and changes the set wavelength in accordance with the amount of wavelength change calculated. As a result, various aberrations of the projection optical system PL are simultaneously corrected, and the main controller 50 irradiates the laser beam on the reticle R and performs exposure, that is, transfers the reticle pattern onto the wafer W via the projection optical system PL, while performing wavelength stabilizing control using the beam monitor mechanism 164 with the changed set wavelength as a reference to maintain the center wavelength of the laser beam to the predetermined set wavelength without fail. In this case, exposure can be precisely performed, in a state as if there were no change in environment from the standard state (that is, a state where the variation amount in optical performance is cancelled out).

[0272]

Also, with the exposure apparatus 10 in the embodiment, each time the set wavelength is changed, the main controller 50 corrects the change in image forming characteristics excluding the environmental change of the projection optical system PL that is corrected by changing the set wavelength, by driving the driving elements 74a, 74b, and 74c via the image forming characteristics correction controller 78. With this

operation, a large part of the environmental change in the image forming characteristics of the projection optical system PL is corrected by the change in set wavelength described above, and the remaining environmental change, irradiation change, temperature change, and the like of the projection optical system PL is corrected by driving the driving elements 74a, 74b, and 74c with the image forming characteristics correction controller 78. As a consequence, exposure with high precision is performed in a state where the image forming characteristics of the projection optical system PL is almost completely corrected.

[0273]

In addition, with the exposure apparatus 10 related to the embodiment, the reticle R is illuminated by the illumination optical system 12 with the ultraviolet light (the wavelength: 193nm or 157nm) emitted from the wavelength conversion portion 163 of the light source unit 16 as the illumination light for exposure, and the pattern formed on the reticle R is transferred onto the wafer W. In this case, the light source unit 16 can control the light amount of the ultraviolet light irradiated on the reticel R depending on the requirements, therefore, as a consequence, the required exposure amount control can be achieved.

[0274]

Further, with the exposure apparatus 10, the light generating portion 160 generates a pulse light by

converting light with a single wavelength generated in the light source 160A into the pulse light by the EOM160C, and the pulse light is amplified by the light amplifying portion 161 including the fiber amplifier. And when the control unit 50 irradiates the amplified pulse light on the reticle R and the wafer W is exposed via the reticle, at least one of the frequency and the peak power of the pulse light is controlled by the light amount controller 16C via the EMO160C in accordance with a position on the wafer of the area subject to exposure, that is, a position on the wafer of each shot area or a position of an area illuminated with a slit-shaped illumination area within each shot area. With this operation, the light amount irradiated on the reticle R, and furthermore, the exposure amount on the wafer is controlled with high precision. Accordingly, constantly appropriate exposure amount control becomes possible regardless of a position on the wafer of an area subject to exposure, and it becomes possible to transfer a mask pattern on the substrate with high accuracy. That is, correction of process variation of each shot area on the wafer and improvement in line width uniformity within each shot area become possible.

[0275]

With the exposure apparatus related to the embodiment, when the main controller 50 irradiates the amplified pulse light on the reticle R as described above and the wafer W is exposed via the reticle R, the light amount of

the pulse light emitted from the light amplifying portion 161 is controlled via the light amount controller 16C by individually turning on/off the light output from each optical path 172_n. With this operation, the light amount irradiated on the reticle R, and furthermore, the exposure amount on the wafer is controlled step-by-step in a wide range. Accordingly, exposure amount control depending on difference in resist sensitivity and the like of each wafer when repeatedly performing exposure on a plurality of substrates becomes possible. Thus, it becomes possible to transfer a reticle pattern on the wafer with a required accuracy without being affected by the resist sensitivity and the like.

[0276]

In the embodiment above, to control the oscillation wavelength of the laser light source 160A, the laser beam is monitored by the beam monitor mechanism 164 arranged immediately after the laser light source 160A. The present invention, however, is not limited to this, and as is shown in Fig. 5 in dotted lines, the laser beam may be separated within the wavelength conversion portion 163 (or downstream in the wavelength conversion portion 163), and may be monitored by the beam monitor mechanism 183, which is similar to the beam monitor mechanism 164. And, the main controller 50 detects whether the wavelength conversion is performed accurately based on the monitoring results of the beam monitor mechanism 183, and based on the detection results may feedback control the

laser controller 16B. Naturally, the monitoring results of both beam monitor mechanisms may be used to perform oscillation wavelength control of the laser light source 160A. Furthermore, when the set wavelength is changed to correct the environmental change (for example, including at least the atmospheric pressure) of the projection optical system PL, the set wavelength may be changed to the detection reference wavelength of the etalon element structuring the beam monitor mechanism 183.

[0277]

Instead of utilizing the temperature dependence of the resonance wavelength of the wavelength detection unit in the embodiment described above, the resonator length of the Fabry-Perot etalon structuring the wavelength detection unit may be made variable with the piezo element and the like, and the resonator length dependence of the resonance wavelength may be utilized. This allows wavelength conversion at a high speed.

[0278]

The number of fibers structuring a bundle fiber is 128 in the embodiment above, however, the number may be any number, and the number may be determined depending on specification (illuminance on a wafer), and optical performance, that is, transmittance of an illumination optical system and projection optical system, conversion efficiency of a wavelength conversion portion, output of each fiber and the like required in a product to which the light source unit related to the present invention is

applied, for example, an exposure apparatus. Furthermore, the wavelength of the ultraviolet light is set almost the same as that of the ArF excimer laser or the F_2 laser in the embodiment above, however, the set wavelength may be of any wavelength, and the oscillation wavelength of the laser light source 160A, the structure of the wavelength conversion portion, and the magnification of the harmonic wave may be decided according to the set wavelength. As an example, the set wavelength may be set in accordance with the design rule (such as the line width and pitch) of the pattern to be transferred onto the wafer, moreover, on deciding the set wavelength, the exposure conditions and the type of reticle (whether the reticle is the phase shift type or not) previously referred to may be considered.

[0279]

In addition, although it is not specifically referred to in the description above, with the exposure apparatus which performs exposure using the wavelength of 193nm and under as in the embodiment, measures such as filling or creating a flow of clean air that has passed through a chemical filter, dry air, N_2 gas, or inert gas such as helium, argon, or krypton in the passage of the exposure beam, or vacuuming the passage of the exposure beam, need to be taken.

[0280]

The exposure apparatus in the embodiment above is made by assembling various subsystems including elements

defined in the claims of the present application so as to keep a predetermined mechanical precision, electrical precision, and optical precision. In order to ensure these areas of precision, prior to and after the assembly, adjustment is performed on various optical systems to attain a predetermined optical precision, adjustment is performed on various mechanical systems to attain a predetermined mechanical precision, and adjustment is performed on various electrical systems to attain a predetermined electrical precision, respectively. The process of incorporating various subsystems into an exposure apparatus includes mechanical connection of various subsystems, by wiring electrical circuits, piping pressure circuits, and the like. Obviously, before the process of incorporating various subsystems into an exposure apparatus, the process of assembling the respective subsystems is performed. After the process of assembling various subsystems into the exposure apparatus is completed, total adjustment is performed to ensure preciseness in the overall exposure apparatus. The exposure apparatus is preferably made in a clean room in which temperature, degree of cleanliness, and the like are controlled.

[0281]

Also, in the embodiment above, the case has been described when the light source unit related to the present invention is used in a scanning exposure apparatus based on the step-and-scan method, however, the

light source unit related to the present invention can be applied in units besides the exposure apparatus, for example, in a laser repair unit used to cut off a part of a circuit pattern (such as a fuse) formed on a wafer. In addition, the light source unit in the present invention can also be applied to inspection units using visible light or infrared light. And in this case, there is no need to incorporate the wavelength conversion portion into the light source. That is, the present invention is also effective with not only the ultraviolet laser unit, bus also with the laser unit that generates a fundamental wave in the visible light region or the infrared light region having no wavelength conversion portion. In addition, the present invention is not limited to the scanning exposure apparatus based on the step-and-scan method, and can be suitably applied to the static exposure type, for example, to the exposure apparatus based on the step-and-repeat method (such as the stepper). Furthermore, the present invention can also be applied to the exposure apparatus based on the step-and-stitch method, to the mirror projection aligner, and the like.

[0282]

The projection optical system and the illumination optical system referred to above in the embodiment, are mere examples, and it is a matter of course that the present invention is not limited to these. For example, the projection optical system is not limited to the refraction optical system, and a reflection system made

up of only reflection optical elements or a reflection refraction system (a catadioptric system) that is made up of both the reflection optical elements and the refraction optical elements may be employed. With the exposure apparatus using vacuum ultraviolet light (VUV light) having the wavelength of around 200 nm and under, the use of the reflection refraction system can be considered as a projection optical system. As the projection optical system of the reflection/refraction type, for example, a reflection/refraction system having a beam splitter and concave mirror as reflection optical elements, which details are disclosed in, for example, Japanese Patent Laid Open No.08-171054, and Japanese Patent Laid Open No. 10-20195 can be used. Or, the reflection/refraction system having a concave mirror and the like as reflection optical elements without using any beam splitter, which details are disclosed in, for example, Japanese Patent Laid Open No.08-334695 and Japanese Patent Laid Open No. 10-3039 can also be used.

[0283]

Besides the systems referred to above, the reflection/refraction system in which a plurality of refracting optical elements and two mirrors (a concave mirror serving as a main mirror, and a sub-mirror serving as a back-mirror forming a reflection plane on the side opposite to the incident plane of a refracting element or a parallel flat plate) are arranged on the same axis, and an intermediate image of the reticle pattern formed by

the plurality of refracting optical elements is re-formed on the wafer by the main mirror and the sub-mirror, may be used. The details of this system is disclosed in, U.S. Patent No. 5,488,229, and the Japanese Patent Laid Open No. 10-104513. In this reflection/refraction system, the main mirror and the sub-mirror are arranged in succession to the plurality of refracting optical elements, and the illumination light passes through a part of the main mirror and is reflected on the sub-mirror and then the main mirror. It then further proceeds through a part of the sub-mirror and reaches the wafer.

[0284]

In addition, with the embodiment above, the fly-eye lens system is used as the optical integrator (homogenizer), however, instead of this arrangement, the rod integrator may be used. In the illumination optical system that uses the rod integrator, the rod integrator is arranged so that its outgoing surface is almost conjugate with the pattern surface of the reticle R, therefore, for example, the fixed reticle blind 30A and the movable reticle blind 30B may be arranged in the vicinity of the outgoing surface of the rod integrator.

[0285]

Of course, the present invention can be suitably applied to not only the exposure apparatus used to manufacture a semiconductor device, but also to the exposure apparatus used to manufacture a display including the liquid crystal display device that

transfers the device pattern onto a glass plate, to the exposure apparatus used to manufacture a thin-film magnetic head that transfers the device pattern onto a ceramic wafer, and to the exposure apparatus used to manufacture a pick-up device (such as a CCD), and the like.

[0286]

<<Device Manufacturing Method>>

[0287]

A device manufacturing method using the exposure apparatus described above in a lithographic process will be described next.

[0288]

Fig. 7 is a flow chart showing an example of manufacturing a device (a semiconductor chip such as an IC or LSI, a liquid crystal panel, a CCD, a thin magnetic head, a micromachine, or the like). As shown in Fig. 7, in step 201 (design step), function/performance is designed for a device (e.g., circuit design for a semiconductor device) and a pattern to implement the function is designed. In step 202 (mask manufacturing step), a mask on which the designed circuit pattern is formed is manufactured. In step 203 (wafer manufacturing step), a wafer is manufactured by using a silicon material or the like.

[0289]

Next, in step 204 (wafer processing step), an actual circuit and the like is formed on the wafer by

lithography or the like using the mask and wafer prepared in steps 201 to 203, as will be described later. In step 205 (device assembly step), a device is assembled using the wafer processed in step 204. Step 205 includes processes such as dicing, bonding, and packaging (chip encapsulation) depending on the requirements.

[0290]

Finally, in step 206 (inspection step), a test on the operation of the device manufactured in step 205, durability test, and the like are performed. After these steps, the device is completed and shipped out.

[0291]

Fig. 8 is a flow chart showing a detailed example of step 204 described above in manufacturing the semiconductor device. Referring to Fig. 8, in step 211 (oxidation step), the surface of the wafer is oxidized. In step 212 (CVD step), an insulating film is formed on the wafer surface. In step 213 (electrode formation step), an electrode is formed on the wafer by vapor deposition. In step 214 (ion implantation step), ions are implanted into the wafer. Steps 211 to 214 described above constitute a pre-process for the respective steps in the wafer process and are selectively executed in accordance with the processing required in the respective steps.

[0292]

When the above pre-process is completed in the respective steps in the wafer process, a post-process is executed as follows. In this post-process, first, in step

215 (resist formation step), the wafer is coated with a photosensitive agent. Next, as in step 216 (exposure step), the circuit pattern on the mask is transcribed onto the wafer using the exposure apparatus 10 described above. Then, in step 217 (developing step), the exposed wafer is developed. In step 218 (etching step), an exposed member on a portion other than a portion where the resist is left is removed by etching. Finally, in step 219 (resist removing step), the unnecessary resist after the etching is removed.

[0293]

By repeatedly performing these pre-process and post-process steps, multiple circuit patterns are formed on the wafer.

[0294]

As described above, according to the device manufacturing method of the embodiment, exposure is performed using the exposure apparatus 10 in the embodiment above in the exposure process (step 216). Therefore, by improving the exposure accuracy, a device with high integration can be manufactured with high yield.

[0295]

[EFFECT OF THE INVENTION]

As have been described above, with each invention according to Claims 1 to 6, there can be provided a wavelength stabilizing control method in which the central wavelength of a laser beam can be maintained at a predetermined set wavelength without fail.

[0296]

In addition, with each invention according to Claims 7 to 13, there can be provided a light source unit which can maintain the central wavelength of a laser beam at a predetermined set wavelength without fail

[0297]

In addition, with each invention according to Claims 14 and 15, there can be provided an exposure method in which exposure can be performed with high accuracy without being affected by temperature change and the like in the atmosphere.

[0298]

In addition, with each invention according to Claims 16 to 23, there can be provided an exposure apparatus which can perform exposure with high accuracy without being affected by temperature change and the like in the atmosphere.

[0299]

In addition, with each invention according to Claims 24 and 25, there can be provided a device manufacturing method which can improve the productivity of the microdevice with high integration.

[0300]

In addition, with the invention according to Claim 28, there is the effect of performing exposure with high accuracy without depending on the change in the sensitivity properties of the photosensitive agent accompanying the change of the center wavelength of

energy beam.

[BRIEF DESCRIPTION OF THE DRAWING]

[FIG. 1]

Fig. 1 is a schematic view showing the configuration of the exposure apparatus of the embodiment in the present invention.

[FIG. 2]

Fig. 2 is a block diagram showing the internal structure of the light source unit in Fig. 1 with the main control unit.

[FIG. 3]

Fig. 3 is a schematic view showing the arrangement of the light amplifying portion in Fig. 2.

[FIG. 4]

Fig. 4 is a sectional view showing the bundle-fiber formed by bundling the output end of the fiber amplifiers arranged at a final stage that structure the light amplifying portion.

[FIG. 5]

Fig. 5 is a schematic view showing the fiber amplifiers structuring the light amplifying portion in Fig. 2 and its neighboring portion, with a part of the wavelength conversion portion.

[FIG. 6]

Fig. 6(A) is a view showing an arrangement example of a wavelength conversion portion which generates an ultraviolet light having a wavelength of 193nm by

converting the wavelength of a reference wave emitted from the output end of the bundle-fiber 173 that has the wavelength of 1.544μm to an eighth-harmonic wave using the nonlinear optical crystal, and Fig. 6(B) is a view showing an arrangement example of a wavelength conversion portion which generates an ultraviolet light having a wavelength of 157nm by converting the wavelength of a reference wave emitted from the output end of the bundle-fiber 173 that has the wavelength of 1.57μm to a tenth-harmonic wave using the nonlinear optical crystal.

[FIG. 7]

Fig. 7 is a flow chart explaining an embodiment of a device manufacturing method according to the present invention.

[FIG. 8]

Fig. 8 is a flow chart showing the processing in step 204 in Fig. 7.

[DESCRIPTION OF REFERENCED LETTERS/NUMERALS]

10	Exposure apparatus
12	Illumination optical system (Optical system)
16	Light source unit
50	Main controller (First control unit, Second control unit, Third control unit, A part of image forming characteristics correction unit)
51	Memory (Storage Unit)
74a, 74b	Driving element (A part of image forming

	characteristics correction unit)
77	Environmental sensor
78	Image forming characteristics correction controller (A part of image forming characteristics correction unit)
160A	DFB semiconductor laser (Laser light source)
163	Wavelength conversion portion (Wavelength conversion unit)
164	Beam monitor mechanism (Wavelength detection unit)
165	Absorption cell (Absolute wavelength provision source)
168_n	Fiber amplifier
171_n	Fiber amplifier
W	Wafer (Substrate)
PL	Projection optical system (Optical system)
R	Reticle (Mask)

[DOCUMENT NAME] ABSTRACT

[ABSTRACT]

[PROBLEMS TO BE SOLVED]

To provide a light source unit which can maintain the center wavelength of a laser beam at a predetermined set wavelength without fail.

[SOLUTION]

A temperature dependence map including temperature dependence data of a detection reference wavelength of a beam monitor mechanism 164 is stored in a memory. And, a main controller 50 performs an absolute wavelength calibration to make the detection reference wavelength of the beam monitor mechanism 164 coincide with an absolute wavelength of an absorption cell 165, and also performs a set wavelength calibration to make the detection reference wavelength coincide with a set wavelength based on the temperature dependence map. Therefore, the detection reference wavelength of the beam monitor mechanism can be accurately set to the set wavelength without fail at all times. So, even if the atmosphere of the beam monitor mechanism such as the temperature changes, a wavelength stabilizing control which securely maintains the center wavelength of the laser light source 160A at a predetermined set wavelength using the beam monitor mechanism becomes possible, without being affected by the change.

[DRAWING] FIG. 2

Fig. 1

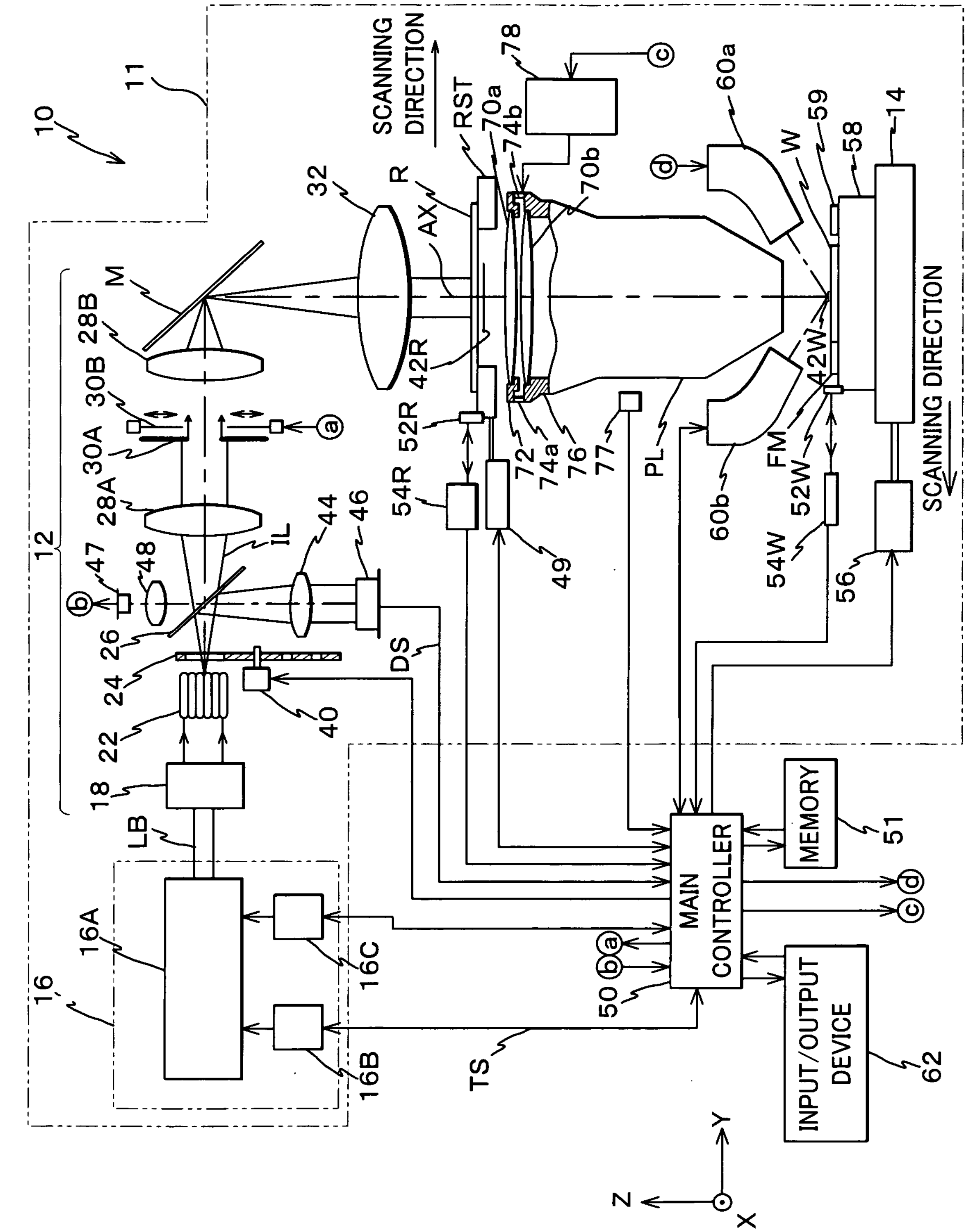

10
11
12
16
16A
16B
16C
18
22
24
26
28A
28B
30A
30B
32
40
44
46
47
48
49
LB
IL
DS
TS
M
R
RST
AX
42R
52R
54R
70a
70b
74b
72
74a
76
77
78
PL
SCANNING DIRECTION
60a
60b
W
59
58
14
42W
FM
52W
54W
56
MAIN CONTROLLER
50
MEMORY
51
INPUT/OUTPUT DEVICE
62
Z
Y
X

Fig. 2

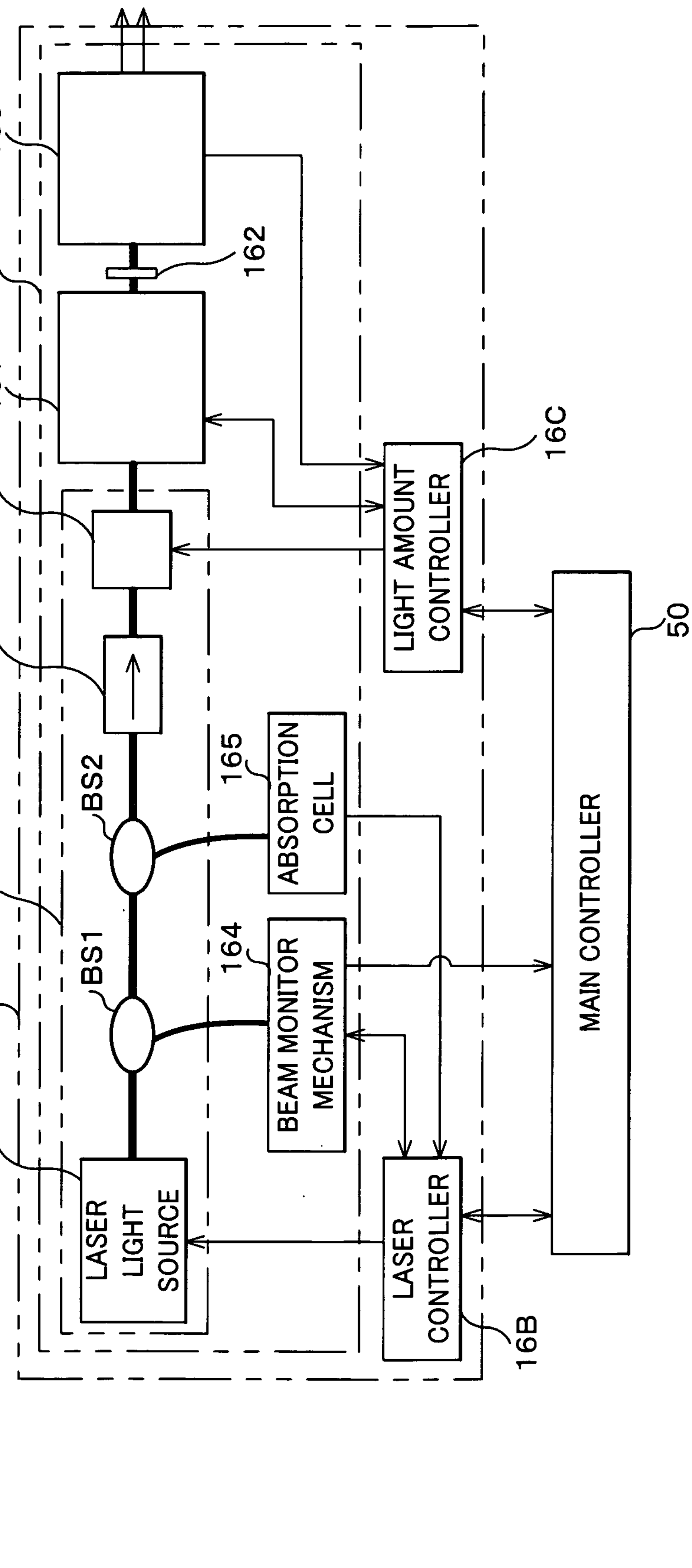

16
16A
160
160A
LASER LIGHT SOURCE
BS1
BS2
160B
160C
161
162
163
164
BEAM MONITOR MECHANISM
165
ABSORPTION CELL
LASER CONTROLLER
16B
LIGHT AMOUNT CONTROLLER
16C
MAIN CONTROLLER
50

Fig. 3

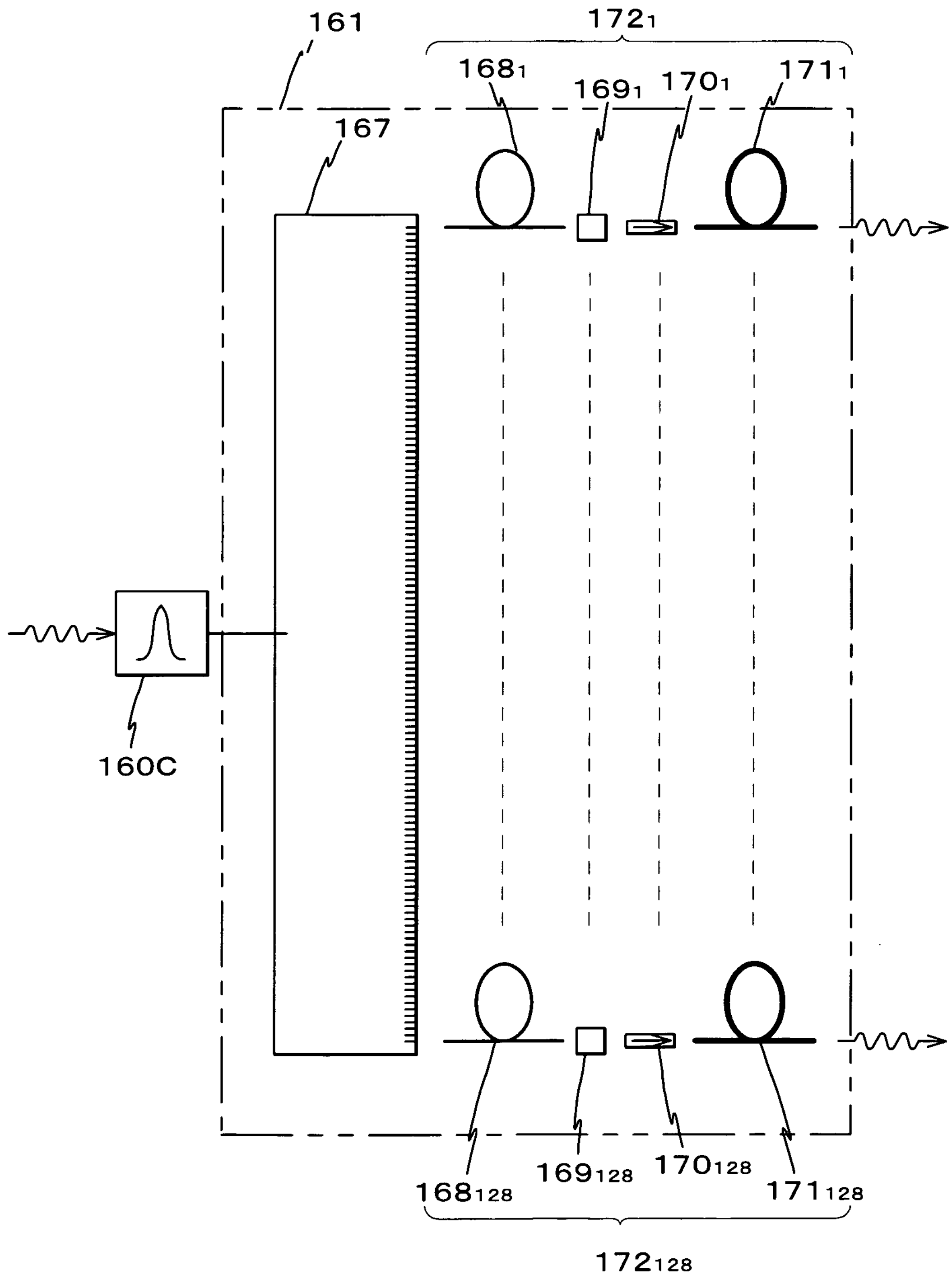

161
172_1
168_1
169_1
170_1
171_1
167
160C
168_{128}
169_{128}
170_{128}
171_{128}
172_{128}

Fig. 4

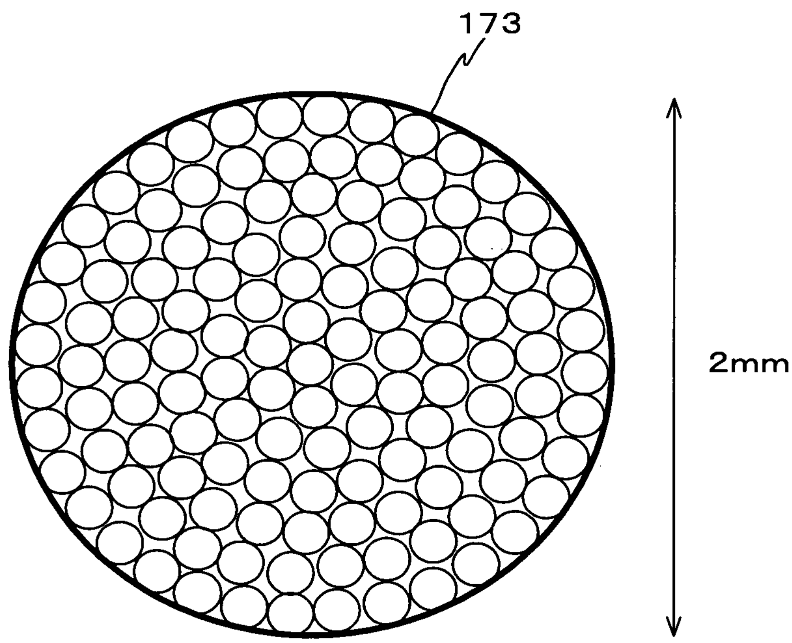


Fig. 5

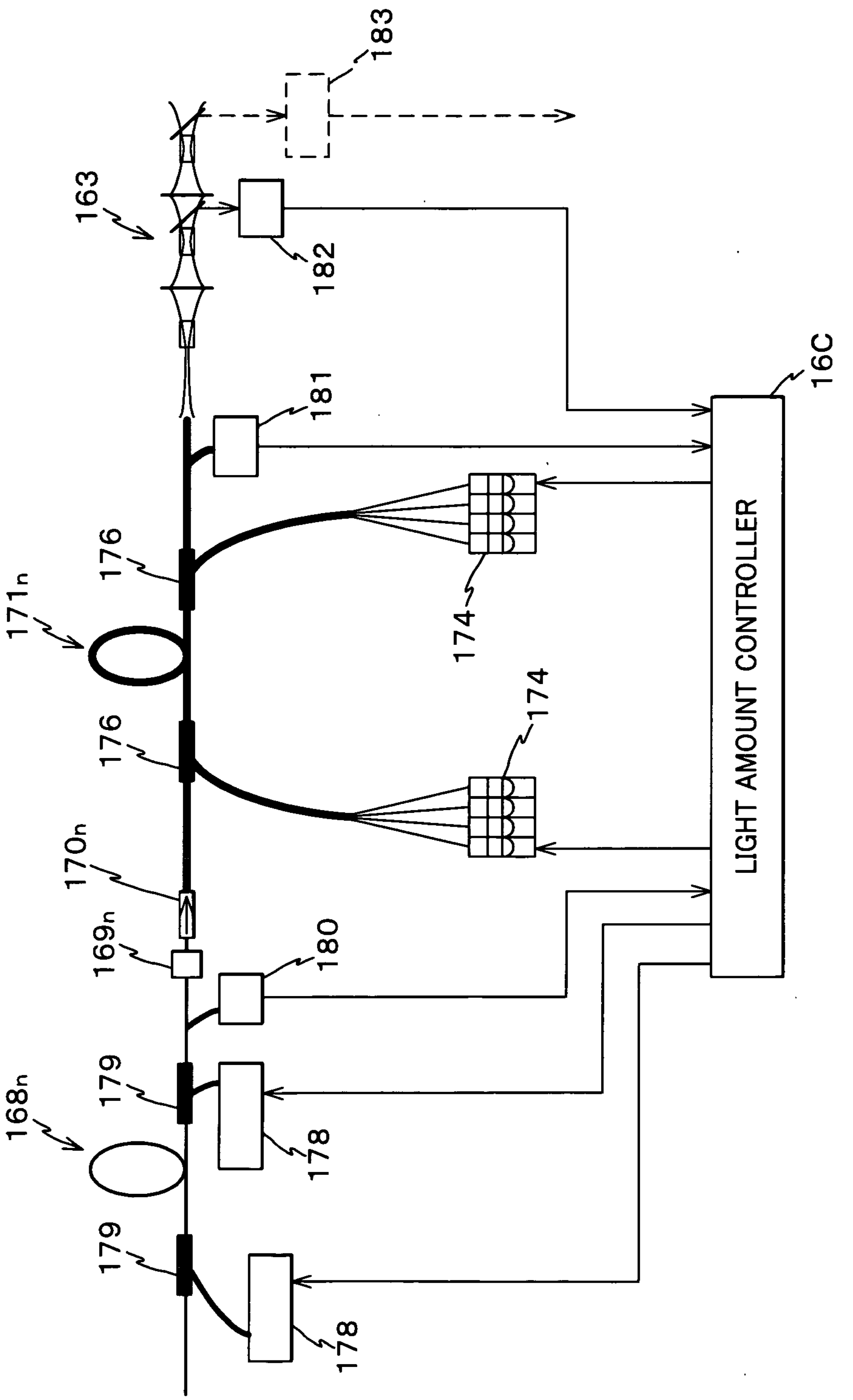

163
183
182
181
16C
176
171n
174
176
174
170n
169n
180
179
168n
178
179
178
LIGHT AMOUNT CONTROLLER

Fig. 6

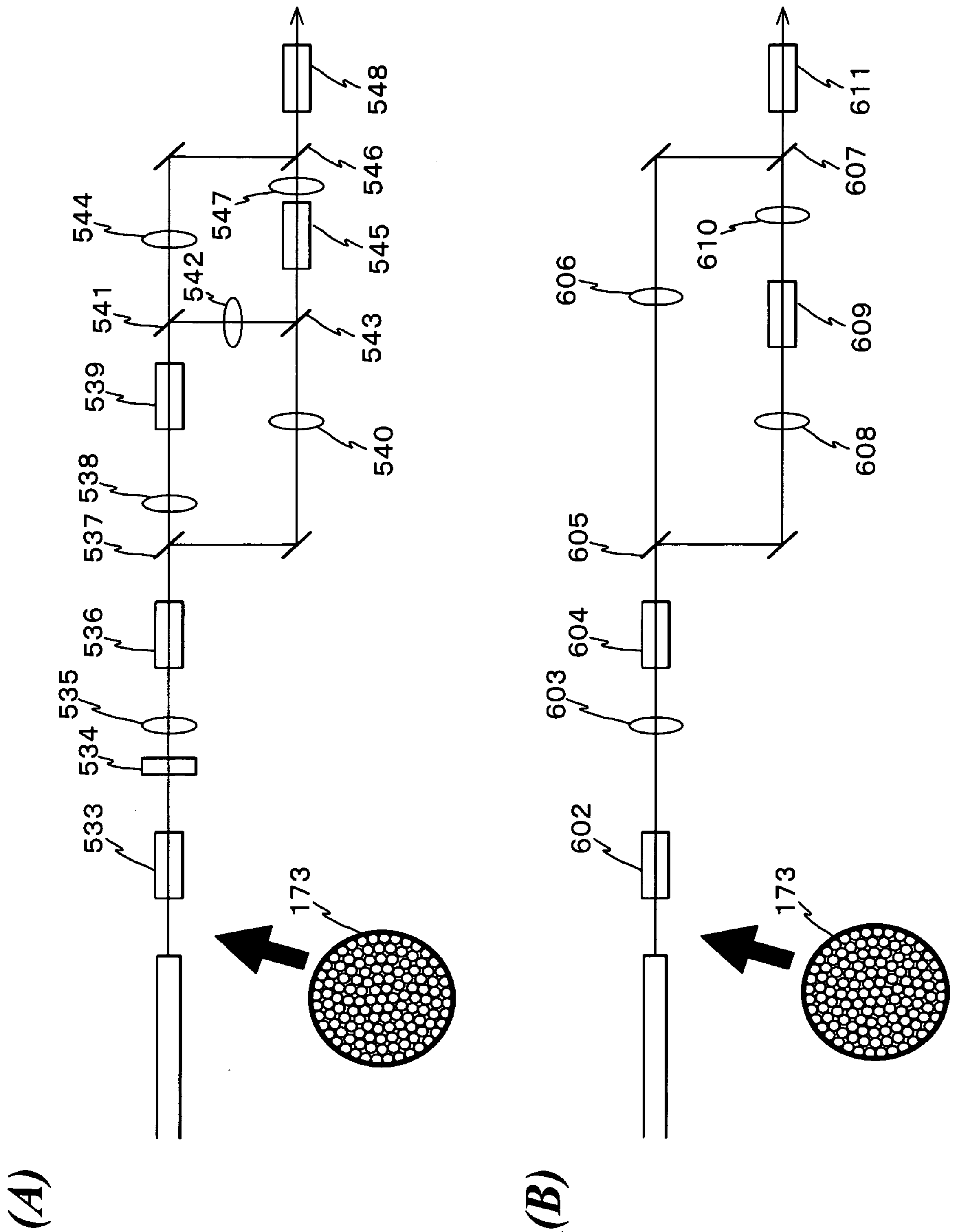

(A)
173
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
(B)
173
602
603
604
605
606
607
608
609
610
611

Fig. 7

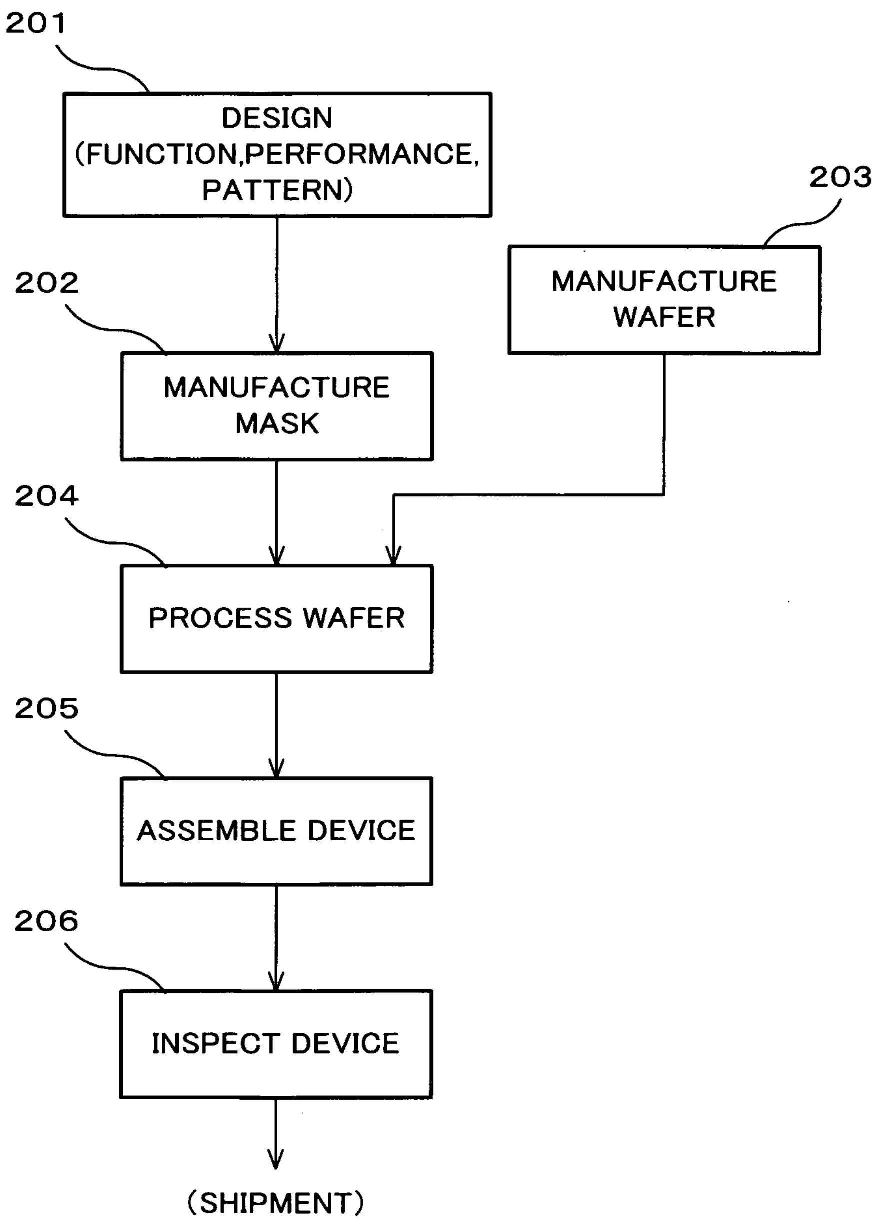
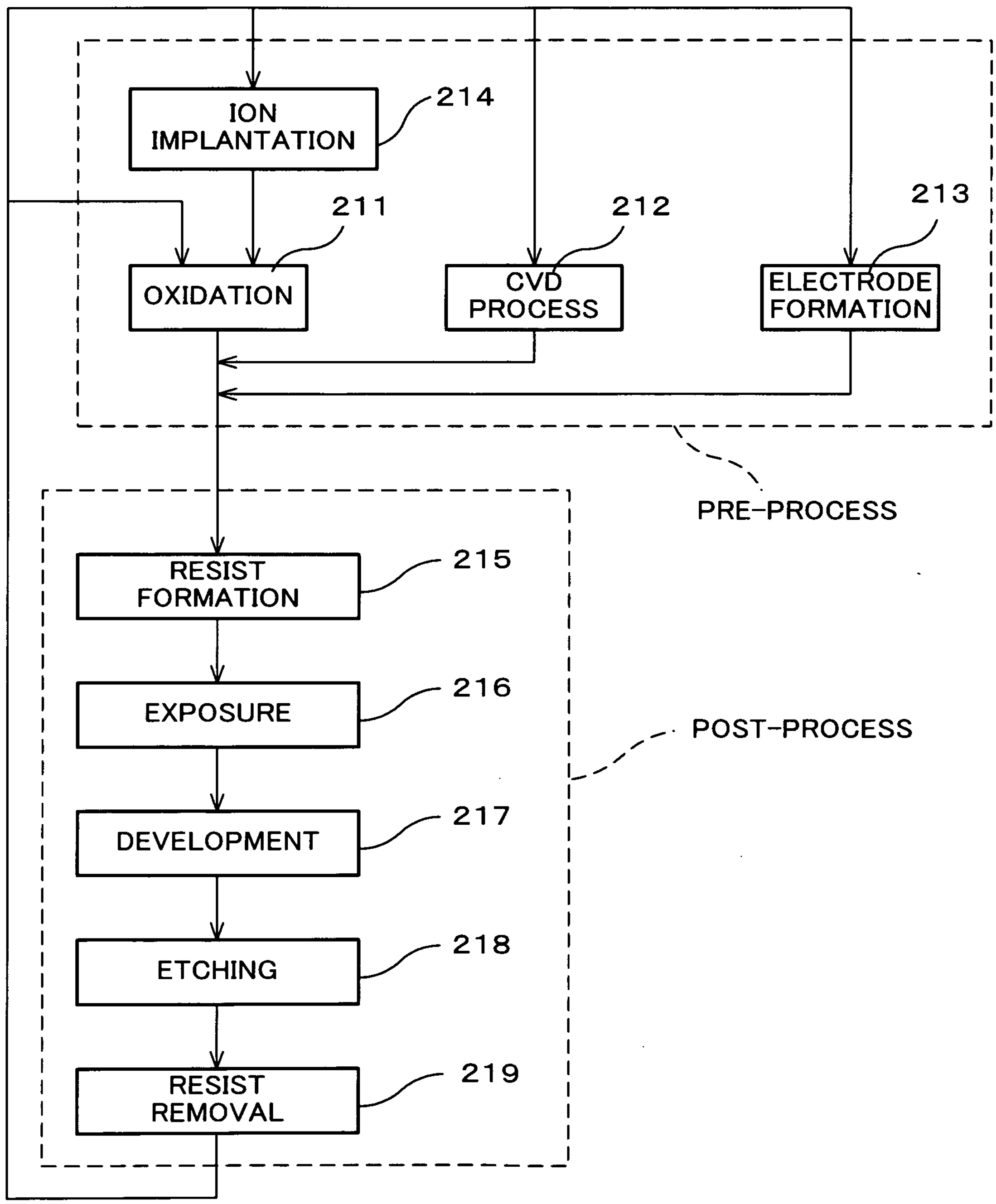

201
DESIGN
(FUNCTION,PERFORMANCE,
PATTERN)
203
MANUFACTURE
WAFER
202
MANUFACTURE
MASK
204
PROCESS WAFER
205
ASSEMBLE DEVICE
206
INSPECT DEVICE
(SHIPMENT)

Fig. 8


ION IMPLANTATION
214
OXIDATION
211
CVD PROCESS
212
ELECTRODE FORMATION
213
PRE-PROCESS
RESIST FORMATION
215
EXPOSURE
216
POST-PROCESS
DEVELOPMENT
217
ETCHING
218
RESIST REMOVAL
219